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Proceedings
Ocean Model Workshop
Held January 15-17, 1992

Department of Fisheries and Oceans

Physical and Chemical Sciences Branch
Scotia-Fundy Region
Department of Fisheries and Oceans

Bedford Institute of Oceanography
P.O. Box 1006
Dartmouth, Nova Scotia
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Canadian Technical Report of Hydrography and Ocean Sciences

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1992

PROCEEDINGS
OCEAN MODEL WORKSHOP
HELD JANUARY 15-17, 1992

Physical and Chemical Sciences
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Bedford Institute of Oceanography
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  - Wave Modelling Group
- Marine Spill Response Corporation
- National Energy Board
- Environmental Studies Research Funds
- Environment Canada
  - Office of the Science Advisor
  - Ice Branch, Atmospheric Environment Service
- Department of Fisheries and Oceans

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ABSTRACT

Department of Fisheries and Oceans. 1992. Ocean Model Workshop Proceedings. Can. Tech. Report of Hydrog. and Ocean Sciences Reprt No. 140:xiv+395.

The Panel on Energy Research and Development (PERD)-sponsored Ocean Model Workshop was held at the Bedford Institute of Oceanography, January 15-17, 1992. Approximately 100 participants from research institutions, government, and private industry attended the Workshop. While the focus of the Workshop was PERD research status and priorities in the areas of sea ice, waves, currents, and oil spill trajectory modelling, international participation provided a broader perspective to the Workshop objectives.

Dedicated sessions were held for each of the four subject areas (sea ice, waves , current and oil spill trajectory modelling), with invited speakers representing users, regulatory agencies, model operators, and researchers addressing the Workshop objectives. The proceedings are organized to reflect the four subject areas with a summary by the session chairman/rapportuer providing a conclusion to each part of the proceedings.

In preparation for the Workshop, PERD funded two state of the art reviews which looked at ocean modelling in Canada (Nazarenko and Desrochers, 1991 and Godon *et al*, 1991). The purpose of these reviews was to provide a baseline from which to initiate discussion with Workshop participants encouraged to comment and suppliment the two reviews. The reviews, along with comments arising from the Workshop, have been included with the proceedings.

RÉSUMÉ

Department of Fisheries and Oceans. 1992. Ocean Model Workshop Proceedings. Can. Tech. Report of Hydrog. and Ocean Sciences Reprt No. 140:xiv+395.

L'atelier sur la modélisation des océans, parrainé par le Groupe interministériel de recherche et d'exploitation énergétiques (GRDE), a été tenu à l'Institut océanographique de Beford du 15 au 17 janvier 1992. Une centaine de personnes représentant des institutions de recherche, des gouvernements ou le secteur privé ont participé à l'atelier. L'accent avait été mis sur l'état et les priorités du GRDE dans les domaines de la modélisation des glaces de mer, des vagues, des courant et de la trajectoire des déversements d'hydrocarbures, mais le caractère international de la participation a donné lieu à un élargissement des objectifs de l'atelier.

Une séance a été consacrée à chacun des quatre domaines d'étude (modélisation des glaces de mer, des vagues, des courants et des trajectoires des déversements d'hydrocarbures). Des conférenciers invités représentant des utilisateurs, des organismes de réglementation, des exploitants de modèles et des chercheurs on traité des objectifs de l'atelier. Le compte rendu est divisé en fonction des quatre domaines traités et l'on trouve à la fin de chacune de ces parties un résumé de la séance et une conclusion rédigés par le président ou le rapporteur.

Le GRDE a financé deux études de l'état actuel de la modélisation des oéans au Canada (Nazarenko et Desrochers, 1991 et Godon et coll., 1991) dans le cadre de la préparation de l'atelier. Ces études ont servi de base aux discussions des participants à l'atelier à qui l'on a demandé de commenter et de compléter les résultats des études. Ces études, et les remarques faites à leur sujet au cours de l'aterlier, sont inclues dans le compte rendu.

EXECUTIVE SUMMARY

PERD OCEAN MODEL WORKSHOP

INTRODUCTION

In January, 1992 the Panel on Energy Research and Development (PERD) sponsored an Ocean Model Workshop to review existing Canadian modelling capabilities and identify research and development requirements. A second purpose of the Workshop was to identify linkages among model users, developers, and researchers, and between different models, as well as constraints to the implementation of operational models. Finally, it was intended that participants would identify priorities for future research efforts.

While the emphasis was on Canadian issues, international participation was encouraged and in fact, the U.S. Marine Spill Response Corporation was an important sponsor of the Workshop.

The Workshop was structured to include separate sessions on modelling of sea ice, waves, currents and oil spill trajectories. Within each session, the needs, capabilities and concerns of users, regulators, operators and researchers were considered. Two PERD-funded state of the art reviews of modelling capabilities (Nazarenko and Desrochers, 1991 and Godon, McGillivray and Dickins, 1991) provided a basis for discussion. Workshop participants were encouraged to comment on and provide supplementary information to the reviews.

WORKSHOP OBJECTIVES

The following workshop objectives were established by the organizing committee:

- Identify existing and developing research and operational models for ocean waves, sea ice, currents and spill trajectories, considering their status, input requirements and limitations. This will be primarily accomplished through the confirmation and/or amendment of the state-of-the-art reviews that were undertaken prior to the Workshop.

- Identify needs for operational models in the offshore from the perspective of (i) industry, (ii) regulators, (iii) model operators, and (iv) researchers. Short presentations on each of these perspectives will be made at the Workshop.

- Identify constraints to the implementation of operational models given the availability or unavailability of research models in each area. This will be accomplished through general discussion at the Workshop.

- Identify priority areas of research for significant model improvements. This will be accomplished through general discussion at the Workshop.

The following sections of the summary highlight the key elements raised during the four modelling sessions. A brief discussion of issues common to all four modelling disciplines concludes the summary.

SEA ICE MODELLING

Sea ice forecast models support requirements for information concerning a variety of ice characteristics including drift, ice edge location, concentration, growth and decay and pressure. This information is required to support operations on tactical, strategic and long-term scales with the result that requirements of models may differ significantly depending on the application. Specific areas of application include:

- input to design criteria (industry, regulatory agencies);
- specification of operating limits (industry, regulatory agencies); and
- operational planning and support (industry, regulatory agencies).

A review of sea ice modelling from the perspectives of the various interest groups resulted in several issues being identified. These included:

- distinguishing between engineering-oriented ice-structure interaction modelling and operational models which were the focus of this Workshop;
- acknowledgement that models were required to support both commercial activities and the research community in its investigations;
- confirmation of a need for reliable and straightforward forecast information, recognizing that the sophistication of the model and model output is dependent on applications;
- recognition that operational models represent a component in the overall operational ice management system;
- recognition that satellite-derived regional ice information may emphasize operational model development to short-term forecasting on the order of 24-72 hours;
- recognition that improvements in model accuracy and reliability as validated through rigorous model verification are necessary for operational implementation and maintenance of models;
- assessment that model improvements will require better inputs, particularly wind and current information. For operational effectiveness, availability of information in real-time was judged to be essential;
- recognition that assimilation of remotely sensed data offers a means of acquiring input information to drive models in real-time.

Specific findings included:

- an assessment that the importance of wave-ice interaction in ice modelling needs to be investigated;
- a need for improved forecasting of ice type and thickness and ice decay/growth;
- a decision that from the viewpoint of operators and regulatory bodies, previously compiled hindcast ice information may need to be revisited, to consider the impact of climate change on ice design criteria;

In the area of linkages, the Operational Ice Modelling Working Group, formed under PERD Task 6.7 in 1987, includes representation from the four broad groups and was identified as providing a key linkage between operational and research groups. Since its formation, the Working Group has been actively working to promote research and development leading to improved operational ice forecasting capabilities. It was felt that the Group was the best existing vehicle for determining direction for PERD initiatives.

WAVE MODELLING

During the wave modelling session a number of areas of application for both hindcast and forecast models were identified:

- feasibility studies (industry)
- environmental assessment (regulatory agencies)
- drilling criteria (industry)
- design criteria (industry, regulatory agencies)
- climate change impact on design criteria (industry, regulatory agencies)
- operational limits/planning (industry, regulatory agencies, research)
- operational support (industry, regulatory agencies)
- interpretation of physical processes (research)

In applying wave models both model operators and researchers identified several areas of concern such as a need for high quality input data, real-time data availability, the need for in-situ model verification and particulary important, guidance as to the selection of appropriate models for specific applications.

Constraints to implementation of effective operational models were similar. Participants recognized that technically, the required input data was frequently unavailable, of inappropriate quality or could not be assimilated in real-time. Appropriate data for model verification was also limited. Finally, administrative constraints in the form of limited availability of computer and personnel resources also impeded the implementation of operational models.

Identified priority research areas included both presently supported projects and new initiatives:

PRESENTLY SUPPORTED

- assimilation and verification of remotely sensed data;
- improvement of techniques for surface wind analysis and forecasting;
- development of techniques to accommodate wave-current, shallow water, and storm erosion effects into models; and
- transfer of research models to operational status including the development of interactive, workstation-based systems for wind and wave analyses and forecasts.

NEW INITIATIVES

- further analysis of recent severe storm events and associated extremal analysis;
- development of techniques for real-time data assimilation, particularly satellite data (including SAR, scatterometer and altimeter data); and
- analysis of global change impacts on design criteria.

Past efforts to develop linkages between the various interest groups in the wave modelling community have met with considerable success and have led to numerous important events in the development of operational wave models. These linkages should be maintained to ensure continued model refinement and implementation. The important linkages include:

- National Waves Committee (researchers, developers, operators and users);
- PERD Task 6 Environment (researchers, developers, operators and users);
- International Wave Workshop Series (researchers, developers, operators and users);

- International Wave Modelling Group (WAM) (researchers, developers, and operators).

Linkages to be improved or developed include linkages with other modellers (for example wave-ice, wave-current, wave-atmosphere) and linkages with atmospheric modellers such as the Canadian Meteorological Centre/Recherches en prévision numérique. The latter was seen as a means to enhance dialogue in the area of wind data requirements. Finally, it was considered necessary to foster a stronger linkage with the Canadian Space Agency to ensure the remote sensing needs of the wave community are considered in Canada's remote sensing program.

CURRENT MODELLING

Participants in the current modelling session identified numerous requirements for current models:

- definition of design criteria (industry, regulatory agencies);
- specification of operating limits (industry, regulatory agencies);
- input to environmental assessment processes (industry, regulatory agencies);
- input to sea ice, iceberg, wave, and oil spill models (industry, regulatory agencies, research and operators);
- evaluation of scour and sediment transport (industry, regulatory agencies); and
- input to search and rescue efforts (regulatory agencies).

Generally, participants perceived a lack of technical support in the form of programming and computing resources required to implement operational models. It was also felt that the emphasis placed on scientific publication frequently led researchers to neglect the final steps required for the implementation of operational models.

The difficulty in obtaining appropriate input data in near real-time also restricted the development of operational models.

Research considerations and priorities in the area of current modelling included the following:

- identification of appropriate, useful and practical models for a specific application;
- improvement of techniques for data assimilation into models;
- improvement of access to data that inputs to current models (for example, wind and satellite data); and
- attention to near surface currents for input to ice and oil spill modelling.

Several Workshop participants also commented that they would like to see greater accessibility to output from DFO models.

In evaluating linkages in the current modelling community, participants felt that past relationships between researchers and developers (such as BIO scientists and private contractors) had been fruitful in bringing several research models to an operational stage. Examples included recent and ongoing collaborations in the areas of ice and iceberg drift, tidal, wind-forced and mean current modelling. The future of this linkage is in question however, as the termination of supporting funding mechanisms may restrict options for future implementation of operational models.

Comments regarding surface current modelling capabilities pointed to a need for stronger linkages between the research and user communities since this is not presently an area of emphasis within the research community. It was felt that although workshops and the PERD committees are valuable linkages through which the research and operational communities could interact, they did not provide an opportunity for ongoing interaction. With this in mind it was recommended that a current modelling steering group be established to provide an ongoing exchange among all groups in the current modelling community.

OIL SPILL TRAJECTORY MODELLING

Oil spill trajectory modelling has not been a priority area for PERD. At the Workshop it was seen that there was room for greater PERD involvement in this area of modelling particularly as it related to other PERD modelling activities.

The Workshop identified three important roles for oil spill trajectory model information including, 1) determination of the most efficient deployment of resources for containment, protection and clean-up; 2) risk assessment and contingency planning; and 3) spill response training.

Serving these roles, trajectory models have application to aspects of preparedness, response and post-spill activities:

PREPAREDNESS

- response training
- risk assessment
- contingency planning

RESPONSE

- equipment deployment
- closure to traffic
- monitoring

POST-SPILL

- damage claims
- evaluate effectiveness of contingency plan
- anticipatory environmental monitoring for effects

Criteria for an oil spill trajectory model for actual spill response include:

- provision of accurate trajectory prediction;
- suitability under a variety of environmental conditions;
- cost effective;
- presentation of output graphically for ready interpretation;
- provision of information quickly; and
- ease of use.

The Workshop generated considerable discussion as to future research efforts. Among several areas of research, it was generally agreed that better oil fate algorithms were essential to

the improvement of trajectory models. The need for high quality, real-time input data to drive the models was also seen as being an area for further research as was a need for model tailoring for operation at regional scales.

Remote sensing data was seen as offering the greatest opportunity to improve the input data for model initialization. It was noted that remote sensing data also generates information on oceanographic phenomena such as convergence zone locations which can aid in the location of discontinuities in the oil slick and provide information critical to the effectiveness of oil spill clean-up operations.

Adjoint current models were seen as a potential method of assimilating data required for oil spill trajectory model initialization. With further development, these could provide estimation of surface flows across open boundaries and nowcasts and short-term forecasts of surface flows.

Model verification was seen by Workshop participants as an important research priority but one that would be difficult to implement successfully. Concerns were also expressed over the interpretation of comparative model evaluations.

Workshop participants felt that existing linkages between model developers and users were providing an important role in ensuring implementation of operational oil spill trajectory models. During the evening discussion period it was felt there was a need to ensure that model development was consistent with the requirements of regulators and users. A suggestion was made to formalize a working committee, comprised of model developers and users, which could meet periodically to solicit and prioritize research activities that would enhance model development.

GENERAL RESEARCH PRIORITIES

Results from the individual sessions were presented and discussed at a summary period and key points that were common to all modelling disciplines were identified.

Participants agreed that better winds information was required for model input in all areas. It was suggested that a working group on marine winds be formed to translate concerns from this Workshop into a defined research plan. In this regard, establishing a link to the Canadian Meteorological Centre (CMC) was seen as being critical to the working group's success. Val Swail was tasked with making initial contact with CMC.

The need for improved techniques for data assimilation into models was highlighted as a research priority in every session. Further research into the assimilation of remotely sensed data into models was identified to have a high priority. Development addressing these issues would benefit from establishment of ongoing interaction between the various modelling communities.

WORKSHOP CHAIRMAN'S OPENING REMARKS

R.B.L. Stoddart
Physical and Chemical Sciences Directorate
Department of Fisheries and Oceans
Ottawa, Ontario

By way of introduction I would like to summarize the structure and objectives of the Panel on Energy Research and Development (PERD). I will then outline the interests of PERD in sponsoring this ocean modelling workshop, its objectives and intended outputs.

The PERD program is coordinated by the Department of Energy, Mines and Resources. It was established in 1974, and it presently consists of some 12 federal departments and agencies. The PERD budget has fluctuated over the years; it has stabilized at about $90 million since 1986. We look forward to confirmation of the program for 1992/93 and beyond. The overall PERD objective is to "provide the science and technology for a diversified, economically and environmentally sustainable energy economy". The diversification objective is met through the PERD organization into 7 tasks: energy efficiency; coal; fusion; renewable energy and generic environment; alternative transportation fuels; oil, gas and electricity; coordination and international participation. The main focus of Task 6 (oil, gas and electricity) has been on frontier oil and gas in the offshore, and this is where we find the PERD interest in R&D needs for improved wave, sea ice, currents and trajectory models.

PERD Task 6 has recently restructured itself. Ocean modelling concerns are now largely within the Task 6 Environment Committee. The overall objectives of the Environment Committee are :

- to improve forecasting of sea, ice and weather conditions particularly in the frontier regions.
- to develop and enhance the interpretative capability of environmental information to optimize the design of operational programs and offshore structures.
- to increase our knowledge of the potential impact of oil and gas development on the environment.

Almost all PERD projects for ocean wave, sea ice, currents and spill trajectories have the development or improvement of some sort of model as their end objective. By that I mean that technology development, methods development, process research, etc. all tend to be a subset of some improved ocean model predictor. This being said, the PERD Environment Committee is somewhat overwhelmed each year with project proposals having as their ultimate objective a deliverable that is to develop a better ocean model. Hence the purpose of this workshop is to, through state-of-the-art reviews and presentations on requirements:

- identify existing and developing research and operational models.
- identify needs for operational models for:

  - industry

- regulators

- model operators

- researchers

- identify linkages amongst model users.
- identify constraints to the implementation of operational models.
- identify priority areas of research.

Through the workshop we intend to provide guidance to potential project proposers and potential funders on what needs attention in ocean modelling, in an energy development context, in the short, medium and long term. Often the informal contacts and conversations are the best outputs from workshops such as this one; I hope that exchange of information is a meaningful output of this workshop. We plan to publish a set of proceedings of the workshop, including abstracts of all the presentations and a summary of discussion during the workshop. The workshop summary should aid in setting priorities for future PERD modelling efforts and include any generic or specific recommendations that should be provided to the PERD Task 6 Environment Committee.

While this workshop has a distinct PERD flavour, discussions and recommendations should not be restricted to PERD only. The workshop should discuss the entire suite of modelling concerns and we should leave it to PERD to carve off whatever seems appropriate from their perspective; other related programs will have their own priorities. In these days of shrinking budgets we should also allow for joint programs with PERD and Departmental A-Bases, various Green Plan initiatives, the recently announced DSS brokerage service and the Environmental Innovation Program, the Environmental Studies Research Fund, industry, and others.

SEA ICE MODELLING

Chairman: Ken R. Croasdale, Esso Resources Canada Ltd.

Rapporteur: Venkata Nerella, Atmospheric Environment Service

SUMMARY
OF A
STATE OF THE ART REVIEW OF SEA ICE MODELLING

A state of the art review of sea ice modelling in Canada has been carried out, considering the operational requirements and use of ice forecast information, as well as research leading to the refinement of existing models or the development of new models. The review also considered international aspects of sea ice modelling which may have relevance to Canadian activities. A total of 32 models were reviewed and key parameters documented.

Operational needs were evaluated and users were categorized in three main groups: government, industry and regulatory agencies. A variety of applications and specific output requirements determined whether sea ice models were grouped and reviewed as operational or research-oriented. Additionally, models were categorized into five types, reflecting general applications: (1) ice growth and decay; (2) ice edge prediction; (3) small-scale ice behaviour; (4) regional models; and (5) large-scale climate/global models. Linkages that exist within the research community and between it and the operational users were also included in the review.

The review describes user Canadian requirements for ice forecast information and state of the art sea ice modelling capabilities. It is intended that the document can be used as a tool for the determination of future research efforts and directions.

Reference: Nazarenko, D.M. and D. Desrochers. 1991. A State of the Art Review of Sea Ice Modelling. Report prepared by Norland Science and Engineering Ltd. for the Panel on Energy Research and Development - Task 6.7

BACKGROUND

A variety of predictive sea ice models are used operationally to support Canadian marine activities. These models, or products derived from them, are employed by industry, government and regulatory agencies for a variety of applications. The development and refinement of these models is supported through research at government, industry and academic institutions across Canada. The Panel on Energy Research and Development (PERD) supports research to enhance existing operational capabilities through direct funding of modelling research in the areas of sea ice, icebergs, winds, ocean currents, waves and oil spill dynamics. Reflecting the relevance of sea ice modelling to PERD, an operational sea ice modelling working group was organized under PERD task 6.7 in 1987. This group is working to encourage the translation of research results into operational uses.

In recent years, research and development efforts towards improved predictive capabilities for sea ice behaviour have produced a wide variety of models. The models often have different temporal and spatial scales and vary in how they treat the geophysical conditions affecting ice behaviour. In addition, some models have purely research applications, designed to support investigations of physical processes. Others may be operational, oriented to meeting specific needs for forecasting ice conditions. Between these two extremes are a wide variety of models with potential application to a variety of needs.

This paper summarizes a state of the art review of the spectrum of sea ice modelling in Canada. International modelling efforts have also been considered to identify research which may have particular relevance to operational concerns that have been raised in Canada.

REVIEW OBJECTIVES AND APPROACH

A specific objective of the sea ice model review was to detail operational sea ice modelling in Canada and describe how operational needs are being addressed through current research. To achieve this, the approach of the review was to identify:

1) operational users of models and/or forecast products;
2) present and future operational needs;
3) sea ice models in circulation and summarize their stage of development and their potential for operational implementation;
4) the linkages between the research and operational modelling communities; and
5) problem areas which are restricting the translation of research efforts into models which meet operational needs.

It was beyond the scope of this project to provide a detailed evaluation of each model. While the review has identified the important components of the models reviewed, this was done for the purpose of comparison rather than for selection of a model or model component most suitable for a given application. The review provides a synopsis of existing capabilities which can be used as the basis for discussion of existing capabilities and future development efforts.

OPERATIONAL USAGE AND ANTICIPATED REQUIREMENTS

OPERATIONAL USERS

Operational users of ice forecast information can be divided into three main groups: industry, government and regulatory agencies. They are distinguished by the types of activities engaged in and the levels of ice forecast information required.

Presently the Ice Branch of Atmospheric Environment Service (AES) represents the single most important user of operational models in Canada. Ice Branch has a specific mandate to provide ice information support for marine operations.

Through its Meteorological Services Research Branch, AES has also played an important role in model development, implementing the departments Regional Ice Model (RIM) for operational use.

RIM is currently used routinely at the Ice Centre in Ottawa to assist ice forecasters in the preparation of daily ice analysis charts. RIM is also used to generate a 48 hour regional ice forecast for the Alaskan coast. The Ice Centre utilizes a variety of ice growth models to assess ice freeze-up and ice growth at various points along Canadian waterways.

Historically, Ice Branch has acted as both developer and user of ice forecast models and has a continuing interest in model developments to meet their forecast objectives. A description of AES, Ice Branch priorities for sea ice modelling is provided in Table 1.

The main Canadian industry users of ice forecast information are the offshore oil and gas, marine transportation and commercial fishing industries. Within industry, the oil and gas sector has had a direct role in the development of ice forecast models. Despite reduced levels of exploration activity, companies continue to support model development activities. A recent user survey provides a clear indication of where future research efforts should be directed in order to meet the needs of the marine industry generally.

Table 1
List of Modelling-Related Priorities for AES, Ice Branch

LOCATIONS	PRIORITIES	
	ICE-RELATED	MODELLING
Gulf of St. Lawrence; Grand Banks; Labrador Sea; Beaufort Sea	partial ice concentrations; roughness; floe size; ice state; edge location; pressure	-focus on 2-5 day forecasts; -sophisticated thermodynamic models & a better representation of the ocean; -use of ice dynamic models; -need higher resolution models with more appropriate ice rheologies; -incorporate research results.

In that survey, it was the general consensus of the Canadian Petroleum Association (CPA) and its member companies "that PERD funding should focus on the strategic or regional and long-term technical areas while industry accepts its responsibility for the more site specific or tactical information needs". A short list of needs and/or research priorities for the Canadian oil and gas industry is provided in Table 2. The priorities consist of ice detection, ice forecasting and ice management, as well as ice/structure interaction information for a number of operational scenarios in the Grand Banks, Beaufort Sea and High Arctic. Ratings of low, medium or high priority were provided by individual CPA users.

Table 2
Canadian Oil and Gas Industry Priorities for Ice Information

LOCATIONS	OPERATING SCENARIOS	PRIORITIES	
		ICE DETECTION (D); FORECASTING (F) & MANAGEMENT (M)	ICE/STRUCTURE INTERACTION
Grand Banks	-fixed platform -float platform -pipeline -tankers/shipping -exploration	high (D & F) high (D & F) medium high (D) medium	high med/high high low low
Beaufort Sea	-platform -offshore pipeline -tankers/shipping -exploration	low/high low/high high (D) med/high	high high low med/high
High Arctic	-fixed platform -float platform -tankers/shipping -exploration	low high high (D) medium	high medium low low

Beyond potential tanker support for the oil and gas industry, the marine transportation sector operates seasonally in the Canadian Arctic and is an important user of ice information. Within the marine sector there is both the commercial fleet and the Canadian Coast Guard. In

terms of general operational requirements, the kinds of ice information required by the two groups are similar.

For the most part, shipping companies rely on external interpretations of ice conditions for decision making, rather than conducting hands-on data analysis. Similarly, they are seldom in a position to make use of forecast models directly but rely on third-party products for the information they require. An exception to this reliance on outside information is Canarctic Shipping Company Limited which has developed its own ice research group to support marine operations.

The commercial fishing industry also makes use of ice information products to plan trawler activities. Once again, the fishing industry relies on third-party information obtained directly through the Ice Centre and through the Coast Guard Ice Operations Office.

OUTPUT REQUIREMENTS

The necessary requirements for operational forecasting are dependent on:

- the type of activity and/or operation, and
- the geographical domain in which the operations will take place,

while the ability to provide forecasts of sea ice movement from operational models depends on:

- the spatial and temporal scales involved, and
- the accuracy required.

OPERATIONAL CONSIDERATIONS

Most sea ice models have been designed as research tools. Frequently their use is directed towards understanding physical processes rather than forecasting ice conditions to support operational activities.

Aside from difficulties inherent in modelling physical processes, for a model to be used operationally, the following operational constraints also need to be considered:

- The model should have some means of directly incorporating observed and analysed ice information at a point when the model is initialized.

- Forecasts cannot rely heavily on real-time data inputs such as "high-resolution" currents or direct on ice measurements if provision of these data is not possible on a routine basis.

- Constraints imposed by the availability or quality of data required to drive the models or computational factors may require compromises in model formulation.

- Model results must be available in a timely fashion. Computational requirements or the time and effort required to process input data may affect how well a given model can meet operational needs.

OPERATIONAL MODELS REVIEWED

The identification and description of existing operational models was an important component of the review. Recognizing that models have been developed for various applications,

the models reviewed have been organized into five main groups characterizing: ice growth and decay; ice edge position; small-scale ice behaviour; regional ice characteristics; and climatic/global ice behaviour. Several of the models may serve more than one application and since these categories are somewhat artificial, a particular model may fit into more than one group.

A summary of operational sea ice models that were considered in the review is provided in Table 3. The type of model, its applicability and the users and/or model developers were also identified.

Table 3
Summary of Operational Models

Sea Ice Models	Type	Applicability	Users
AES - Regional Ice Model (RIM)	R	O; R	fed. gov't (AES)
AES - FDD Ice Thickness Model	G	O	fed. gov't (AES)
AES - Heat Budget Ice Thickness Prediction Model	G	O	fed. gov't (AES)
AES (Billelo) - N-value Freeze-up Model	G	O	fed. gov't (AES)
AES - Analog Freeze-up and Break-up Method	G	O	fed. gov't (AES)
Amoco/Canmar Ice-Forecasting	S	O	industry
El-Tahan - Ice-Floe Drift Model	E	O	private firm
Seaconsult - Long Range Sea Ice Prediction Model	R	O	fed. gov't (AES)
Kozo - Sea-Ice Movement Forecasting Model	S; R	O	university (USNA/Alaska)
Pritchard - Ice Edge Model	E	O; R	univ./priv./indus. (NPS/firms/ARCO)
NOARL - High-Resolution Sea-Ice Model (RPIPS-B MODEL)	R; E	O; R	U.S. gov't (NORDA)

Type: (G) - Ice Growth; (E) - Ice Edge; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.

RESEARCH AND DEVELOPMENT OF SEA ICE MODELS

As part of the review it was important to document research and development work that is being done, focusing first on efforts in Canada and then on international research. Table 4 provides a summary of the research-oriented models that were reviewed. For each model, model group and stage of development are noted. If documented sensitivity analyses were available, they were noted as well. Finally, the nature of information transfer is provided as a research/operations linkage.

Table 4 Summary and Status of Research Models Reviewed

Sea Ice Model	Type	Stage of Development	Sensitivity Analyses	Research Operations Linkages
AES/Gabison - Thermodynamic Ice Growth and Decay Model	G	D	Y	PUB
Miller - Seasonal Sea Ice Growth Model	G	D	Y	PUB; PRES
Mellor - MIZ Coupled Ice-Ocean Model	E	UK	Y	PUB
Ikeda - Labrador Shelf Dynamic/ Thermodynamic Sea-Ice Model	R	D/U	Y	PUB; PRES
Ikeda - Coupled Ice-Ocean Model	R	U/O	Y	PUB; PRES
IOS - Beaufort Sea Ice-Ocean Model	R	D	N	PRES
Waterloo - Short-Term Sea-Ice Motion Model	R	U/O	Y	PUB
Lemke - Ice/Ocean Model with Mixed Layer Pycnocline Model	R	U/O	Y	PUB
Lu - Mesoscale Sea-Ice Model	R	U/O	Y	PUB
Omstedt - Coupled One-Dimensional Sea Ice-Ocean Model	R	O	Y	PRES
Houssais - Thermodynamic Coupled Ice-Mixed Layer Model	R	UK	N	PRES; PUB
Overland & Pease - Coastal Sea-Ice/Barotropic Ocean Model	R	U/O	Y	PUB
Seaconsult - Long Range Sea Ice Prediction Model	R	O	Y	IR
Simple Steady-State Coupled Ice-Ocean Model	C	U/O	N	IR; PUB; PRES
Hibler Coupled Dynamic/Thermodynamic Model	C,R	U/O	Y	PUB; IR; O; PRES
Hibler & Bryan - Diagnostic Ice-Ocean Model	C	O	Y	PUB; IR
Flato & Hibler - Cavitating Fluid Sea Ice Dynamics Model	C,R	O	Y	PUB
Semtner - Dynamic/Thermodynamic Sea-Ice Model	C	UK	Y	PRES
Semtner - Arctic Sea Ice and Ocean Circulation	C	O	Y	PUB
Parkinson & Washington - Large-scale numerical model of sea-ice	C	U/O	Y	PUB
Walsh & Zwally - Dynamic/Thermodynamic Sea-Ice Model	C	UK	Y	PRES
Riedlinger - Arctic One Dimensional Ice-Ocean Model	C	O	N	PUB

Type: (G) - Ice Growth; (E) - Ice Edge; (R) - Regional; (S) - Small-scale; (C) - Climate.
Stage: (O) - Ongoing; (U) - Updated from previous version; (D) - Discontinued; (UK) - Unknown; (OP) - Operational.
Sensitivity: (Y) - Yes, analyses published; (N) - No, analyses not published.
Linkage: (PUB) - Results published; (IR) - Results in internal report; (PRES) - Results presented at conference/workshop; (O) - Other.

While a detailed description of model parameters was beyond the scope of this project, some basic parameters of the dynamic/thermodynamic models reviewed are presented in Table 5 for comparison purposes.

RELATED RESEARCH EFFORTS

Considerable research presently under-way focuses on specific formulations or parameterizations required to improve ice modelling capabilities. Some of the issues identified by the PERD 6.7 Ice Working Group requiring better parameterization include the following:

- Air/Ice Drag Relationship;
- Ice/Water Drag Relationship;
- Ice Melt;
- Ice Growth;
- Ice Rheology Implementation;
- Surface Roughness/Ice Pressure;
- Ice State; and
- Ice Drift.

Some additional related issues noted during the review which are relevant to operational and research sea ice modelling include:

- Lagrangian versus Eulerian Formulation;
- Remote Sensing Data Assimilation;
- Computational Developments; and
- Standardized Verification Procedures.

LINKAGES WITHIN AND BETWEEN RESEARCH AND OPERATIONS

In addressing the status of operational and research models, linkages to facilitate the transfer of information between researchers and to the operational community cannot be separated from a description of the sea ice models themselves. Reviews of various models revealed the importance of cross-pollination between researcher's that lead to new hybrid models. Similarly, in considering the operational models listed in Table 3, most of them have originated from what was originally a research application.

INTERNAL RESEARCH LINKAGES

From the review of recent and current research efforts, it is clear that interaction and exchange of information between researchers is essential, although it is not as clear how this exchange takes place. Discussions with various researchers suggest that personal communication and a reliance on published material and conference presentation are the main mechanisms for this exchange.

RESEARCH - OPERATION LINKAGES

Perhaps more important to the objectives of this review are the linkages between the research and operations communities. The need for interaction is particularly important given that the researcher and operational user frequently have different priorities in the application of ice models. Typically, a research model provides a tool for better understanding of the physical processes involved in a particular problem.

Table 5
Comparison of Some Basic Model Parameters

Sea Ice Model	Q_a	Q_w	C_a	C_w	P^*
Mellor - MIZ Coupled Ice-Ocean Model	N/A	M	2	3.8	N/A
Ikeda - Labrador Shelf Dynamic/Thermodynamic Sea-Ice Model	V	V	1.2	N/I	0.5
Ikeda - Coupled Ice-Ocean Model	N/I	V	N/I	6	1
IOS - Beaufort Sea Ice-Ocean Model	N/I	N/I	N/I	N/I	N/I
Waterloo - Short-Term Sea-Ice Motion Model	N/A	N/A	1.5	4	2
Lemke - Ice/Ocean Model with Mixed Layer Pycnocline Model	N/A	M	1.2	5-5.5	2.75
Lu - Mesoscale Sea-Ice Model	N/A	N/A	1.55	5.5	2.75
Omstedt - Coupled One-Dimensional Sea Ice-Ocean Model	M	M	N/I	N/I	2
Houssais - Thermodynamic Coupled Ice-Mixed Layer Model	V	V	V	V	N/I
Overland & Pease - Coastal Sea-Ice/Barotropic Ocean Model	N/A	N/A	2.8	1.8	1.6
Simple Steady-State Coupled Ice-Ocean Model	3.5-10.0	5-20	N/A	N/A	N/A
Hibler Coupled Dynamic/Thermodynamic Model	N/I	N/I	1.2	5.5	0.5
Hibler & Bryan - Diagnostic Ice-Ocean Model	N/I	V	V	V	V
Flato & Hibler - Cavitating Fluid Sea Ice Dynamics Model	N/A	V	V	V	V
Semtner - Dynamic/Thermodynamic Sea-Ice Model	N/I	0-275	1.8	1.8	V
Semtner - Arctic Sea Ice and Ocean Circulation	N/I	0-275	1.8	1.8	V
Parkinson & Washington - Large-scale numerical model of sea-ice	V	2-25	2.4	V	V
Walsh & Zwally - Dynamic/Thermodynamic Sea-Ice Model	N/I	2	1.2	5.5	V
Riedlinger - Arctic One Dimensional Ice-Ocean Model	N/I	V	2.7	5.5	N/A

Q_a - Atmospheric Heat Flux (W m^{-2})
Q_w - Oceanic Heat Flux (W m^{-2})
C_a - Air Drag Coefficient ([x 10^{-3}], non-dimensional)
C_w - Water Drag Coefficient ([x 10^{-3}], non-dimensional)
P^* - Ice Strength Constant ([x 10^4], N m^{-2})

M - modelled parameter
V - variable
N/A - not applicable
N/I - insufficient information or not available

For the operational user concern for physical processes is likely secondary, with specific forecast conditions being of primary importance. In this respect, the operational user requires that forecasts be provided in a timely manner, to an acceptable level of accuracy and reliability. The fact that specific requirements may vary with the user application further complicates the relationship between modelling research and operational implementation.

While dialogue may be challenging, both informal and formal linkages between the communities are evident in Canada.

Informal exchange frequently occurs on a personal level but this tends to be narrowly

focused. For example, good "rapport" may be established between two individuals with the result that the operational needs of the one may be accommodated.

Informal linkages may be forged between researchers and operational users as researchers pursue project funding from bodies such as the National Science and Engineering Research Council (NSERC). Demonstrated industry support for a research proposal may be important in the funding application process. At the same time the linkage fosters communication between the two groups that might not otherwise occur.

Formal linkages exist in the form of joint committees and funding bodies. These include PERD Task 6.7. A subcommittee within this body, the Operational Ice Modelling Working Group was formed in 1987 to promote the transfer of existing research to AES, Ice Centre operations and to promote additional research in support of general operational requirements. Committee members are drawn from AES, Bedford Institute of Oceanography (BIO), Institute of Ocean Science (IOS), National Energy Board (NEB) and industry, providing representation from both the operations and research communities. The working group meets regularly and has recently initiated a project to develop standardized model verification procedures and verification data sets for the Beaufort Sea and Labrador Sea/Grand Banks area.

Another linkage exists through the Environmental Studies Research Fund (ESRF). The ESRF is supported through levies on the oil and gas industry and has a mandate to promote environmental research based on industry priorities. Research projects are wide-ranging but have included several ice-related studies.

Finally, few open forums exist in Canada whereby the research and operational ice communities can interact more widely. Conferences such as POAC are the exception. A useful venue of this type was the 1986 East Coast Sea Ice Workshop which included participants from both the operational and research communities. On a smaller scale, the Ice Community Newsletter is published quarterly and provides an information forum for industry, government and academic activity in the area of ice.

WORKSHOP RESPONSE TO THE SEA ICE MODEL REVIEW

A review of operational and research ocean models was prepared for PERD (Status: Research, Development and Operational Use of Ocean Models by Norland Science and Engineering Ltd.) for distribution and comment at this Workshop. While the full review is attached as an appendix to these proceedings, comments from Workshop participants pertaining to the review are noted here.

COMMENTS CONCERNING THE STATE OF THE ART REVIEW

p. A-16 W. Perrie of Bedford Institute of Oceanography (BIO) is conducting research involving the coupling of ice motion to wave and wave-induced currents.

p. A-18 It was noted that Smith and Anderson of Bedford Institute of Oceanography have been actively involved in research to evaluate air/ice drag relationships.

p. A-20 An area of research of importance to sea ice modelling entails the application of microwave remote sensing to sea ice studies. For sea ice observation and model validation, ice data derived from microwave remote sensing such as SAR will play an increasingly important role. A massive effort to prepare the sea ice community for the use of SAR data was launched in 1987 and continued for four years (the Labrador Ice Margin Experiment, Carsey et al., 1989 and Tang et al., 1987). The program involved almost all organizations having an interest in sea ice in central and eastern Canada. Data collected included airborne SAR, ice drift, and ocean current and properties data. The following references provide descriptions of the LIMEX program.

Carsey, F.S., S. Digby-Argus, M. Collins, B. Holt, C.A. Livingstone and C.L. Tang. 1989. Overview of LIMEX '87 Ice Observations. IEEE Transactions on Geoscience and Remote Sensing, 27(5), 468-482.

Tang, C.L., M. Ikeda, S.D. Smith, L. McNutt, S. Digby-Argus, F. Carsey, J. Crawford, B. Holt, A. Lohanick, P. Wadhams, W. Winsor and W.L. Thomas. 1987. Southern Labrador Marginal Ice Zone Study - A Pilot Field Program of LIMEX. Can. Tech. Rep. Hydrog. Ocean Sci., No. 99: iv + 25 pp.

The following pages include a review of sea ice and ocean modelling by M. Ikeda of Bedford Institute of Oceanography. The review, published in 1989 reviews numerical and analytical models of sea ice and ocean circulation and assesses their applicability to the Labrador and Newfoundland shelves.

ADDITIONAL RESEARCH MODELS

Two additional research models were identified:

Model	Status	Description	References
Thermodynamic Seasonal Ice Cover Model (Tang; BIO)	Research discontinued	• Regional model to look at ice edge advance and retreat • Developed for Newfoundland Marginal Ice Zone	Tang, 1991
Short-Term Ice Movement Model (Tang; BIO and Yao; ASA Consulting)	Under development	• Ice edge model developed to evaluate ice-ocean processes	Tang and Yao, in press

REFERENCES

Tang, C.L. 1991. A Two-Dimensional Thermodynamic Model for Sea-Ice Advance and Retreat in the Newfoundland Marginal Ice Zone. J. Geophys. Research, 96(C3), 4,723-4,737.

Tang, C.L. and T. Yao. 1992. A Simulation of Sea ice Motion and Distribution off Newfoundland during LIMEX '87. Atmosphere-Ocean (in press).

OPERATIONAL ICE MODELLING - INDUSTRY REQUIREMENTS

(Abstract Only)

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This presentation provides a brief industry overview of our ice information and operational ice modelling requirements. The broad area of ice detection, ice forecasting and ice management is discussed since a system in its entity is of primary interest to offshore operations. Industry's view of current research requirements in these areas, including operational ice modelling, is provided. These requirements have been obtained from a technical evaluation carried out by the Canadian Petroleum Association and represent a CPA consensus of the views of its member companies. Background information on operating scenarios for the Grand Banks and Beaufort Offshore regions is also provided along with specific detail regarding ice detection, forecasting and management needs on tactical, strategic and long term scales.

Industry recognizes that considerable funding levels have been devoted to ice movement modelling and forecasting and appreciates the importance of this area. However, from a technical standpoint, industry is more likely to combine near real time ice detection and tracking with forecasts and feels that remote sensing should also receive a high priority. We also recognize ongoing communication between industry users and the ice modelling community as a key element in satisfying the overall technical requirement and CPA encourages a continuation of the cooperative dialogue that has been established within the PERD program.

ICE MODELLING - REGULATORY PERSPECTIVE

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REGULATORY BASIS

The Canada Newfoundland Offshore Petroleum Board is responsible for the regulation of petroleum exploration and production operations in the Newfoundland offshore area (NOA). The regulations administered by the Board include provisions relating to safety and to environmental protection. The regulatory basis for ice management is found principally in the following regulations:

Newfoundland Offshore Petroleum Drilling Regulations[1]:

- Section 22 states that each operator shall obtain daily forecasts of "meteorological conditions, including ice movements" during a drilling program.
- Section 64 requires an operator to have contingency plans in place for "any reasonably foreseeable emergency situation, including...hazards unique to the drill site", which in much of the NOA includes pack ice or iceberg encroachment.

Newfoundland Offshore Petroleum Production and Conservation Regulations[2]:

- Section 9.2 contains provisions similar to those of 22 of the Drilling Regulations.
- Section 10.1 requires the operator of a production installation to have contingency plans in place for "abnormal conditions or emergencies that can reasonably be anticipated".

Neither of the above regulations make specific mention of operational ice modelling, nor do the Physical Environmental Guidelines[3] issued pursuant to the former provide any greater detail.

PAST EXPERIENCE AND THE PRESENT CONTEXT

The experience so far in the NOA, has been with exploration only, using either semisubmersibles or drill ships. Both types of platform operation have been carried out on the principle of total avoidance of ice. One result of the foregoing is that the operational need for pack ice modelling has been limited to ice edge modelling. General use has been made by operators of that portion of the AES Regional Ice Model results, as they appeared on the Ice Centre's daily ice analyses. As mentioned in the Norland report[4], the El-Tahan model[5] also was used on some occasions.

Iceberg drift prediction has been attempted through the use of trajectory models of varying degrees of complexity. Trajectory models used to date have been primarily deterministic. Sufficient real-time environmental forcing data (not to mention forecasts of same) seldom have been available to drive the models, and their accuracy has suffered to the point where many industry operational people consider trajectory models at best unreliable and at worst useless. At least one hybrid statistical/deterministic model was developed through ESRF, but has not been

proved operationally; a simulated real-time test is nearing completion.

The use of a "total avoidance" philosophy, coupled with the fact that a given exploratory operation occupies a single geographic location, has meant that operators could compensate for uncertainties in model results by the use of totally reactive, and necessarily more conservative, ice avoidance plans without excessive operational complications and without compromising safety.

THE FUTURE

The advent of production operations at the Hibernia field has the potential to change present-day requirements for ice modelling in the NOA. The Hibernia production installation will be on location year-round. Tanker loading and supply/standby vessel operations will take place in at least partial sea ice coverage. Small/regional model results which include predictions of ice concentration and type, as well as broader-scale ice motion, could be useful for efficient operations planning, both tactical and strategic.

The Hibernia production operation will consist, in the early years, of the GBS platform, two 2-kilometre export pipelines on the seafloor, two loading systems (normally submerged), and, often, a shuttle tanker. While parts of this system will not be as sensitive to all sizes of glacial ice as an exploration operation, the system will be spatially more complex. Iceberg trajectory model results therefore may be more valuable for tactical decision-making than is presently perceived to be the case for exploration drilling on the Northeast Grand Banks.

While somewhat more uncertain, the development of other Grand Banks oilfields could be carried out using floating drilling systems. This would certainly increase the need for accurate, reliable ice models.

In conclusion, while the Board does not require the use of ice models in the same manner that it does for oil spill trajectory models, we recognize the contribution that a good ice model can make towards the optimal performance of any operator's overall ice management plan, as one more tool that can be used to assist in the decision-making process.

REFERENCES

1. Newfoundland Offshore Petroleum Drilling Regulations. Draft: December 1990.

2. Newfoundland Offshore Petroleum Production and Conservation Regulations. Draft: April 20, 1990.

3. Canada Oil and Gas Lands Administration. Canada-Newfoundland Offshore Petroleum Board. Physical Environmental Guidelines for Drilling Programs on Frontier Lands. March 1990.

4. Nazarenko, D. and D. Desrochers, 1991. A State of the Art Review of Sea Ice Modelling. A report prepared by Norland Science and Engineering for the National Energy Board/COGLA 36pp.

5. El-Tahan, M. and G. Warbanski, 1987. Prediction of Short-Term Ice Drift. Proceedings of the Sixth International Offshore Mechanics and Arctic Engineering Symposium, Vol. 4, 393-400.

ICE MODELS USED BY ICE SERVICES

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MODELS - UNDERSTANDING ICE CONDITIONS

Canada's Ice Service provides operational decision support concerning the influence of ice conditions on Maritime operations for sustainable benefits. Such ice services depend on a combination of observations and models to determine and provide information on the evolving ice conditions.

Subjective and objective models are both used. Here we concentrate on the objective ones. The eventual (ideal) goal is that objective environmental models will perfectly describe the ice conditions and their future state.

THE CURRENT USES OF ICE MODELS IN DELIVERING ICE SERVICES

They provide a background on the drift and development (growth and decay) of ice. They provide information on the date for freeze-up at selected sites.

At this time, ice models are used as input to the work of ice analysts and of ice forecasters. They are not yet used for actual forecasts for sea ice. Iceberg models are used to extend the value of observations and for objective forecast iceberg conditions.

WHICH MODELS ARE USED OPERATIONALLY?

SEA-ICE DRIFT: Regional ice model (twice daily) now. General flow pattern OK but many formulations require subjective adjustment when used.

Coupled ice-ocean model soon. Improved resolution and accuracy of motions and development. Possibility of operational objective use.

ICE FREEZE-UP MODELS:

Billelo method for fresh water. Statistically-based on sensible heat flux climatology. Improves as the freeze-up approaches (Great Lakes).
Laevastu Energy Budget Model. Used for marine freeze-up and ice thickness prediction (analysis help).

Other methods used at Ice Centre include freezing degree-days model and analog methods.

THE FUTURE ROLE OF ICE MODELS IN DELIVERING ICE SERVICES

Modelled drift and development (growth and decay) of ice provides the basis for each of on-going assimilation of ice data into ice conditions analysis, ice conditions forecasting and forecast

freeze-up dates.

Ice models will be used to carry out automated data assimilation into ice conditions analyses and to carry out actual ice forecasting and warnings.

CURRENT ICE MODELLING PRIORITIES

1. Implement the coupled ice-ocean model at Canada's Ice Centre.
2. Provide ice model verification data sets and procedures to test new models.
3. Research to provide improved formulations in areas of major concern for the present models, including the modelling of currents, winds, etc.
4. Up-date the current iceberg models in a similar manner.
5. Develop models for other parameters of use in operational decision making such as both general and specific ice and iceberg severity depictions.

CONCLUSIONS

The current state of ice modelling is somewhat like that of weather modelling about 25 years ago. Excellence in ice modelling is a key to future excellence in ice services within a reducing tax based budget.

Investment in ice modelling is key to the future success of ice services.

The goal is to provide better ice information as operational decision support at lower cost.

RESEARCH AND DEVELOPMENT IN SEA ICE MODELLING

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ABSTRACT

Ice modelling research sponsored by PERD in support of ice forecasting in Canada concentrates on two geographical regions: the Beaufort Sea shelf and the Labrador/Newfoundland shelf. The two regions have different ocean, ice-cover and atmospheric conditions and as such, models developed for these regions emphasize different terms specifying the ice/ocean/atmosphere interactions. A single model should thus not be used to predict the ice conditions for these two diverse regions.

Ice/ocean coupled models being developed for ice forecasting range from simple one-dimensional Freezing-Degree day models to three-dimensional ocean/ice coupled models forced by atmospheric conditions. These models are being improved for each of the two geographic regions, their forecast period is being extended and more ice properties are being predicted. Other models are used to study specific processes affecting the ice cover and ocean in order to parameterize these processes in the larger 3-D models.

Although most models couple the ice-cover and ocean, the degree of coupling varies greatly as it depends on the parameter and direction of the coupling process. Bulk eddy parameterization is most commonly used, but their coefficients, which determine the degree of coupling, vary between models. Only when the interactive coupling occurs on turbulent spatial and time scales is the process correctly modelled, but this requires too much oceanographic, ice-cover and atmospheric data to be useful in forecast models. Only research models use turbulent scales to determine the expected range of bulk parameters for use in forecast models.

Research models are run for short and long-term forecast (days to years) in a hind-cast mode, i.e. the results they are predicting are known. In this scenario, data is used to tune the various constants in the model to best fit observed conditions before the model can predict future ice/ocean conditions. Efforts are now under-way to run research models with real-time boundary conditions. On the other hand, operational forecast models use predicted atmospheric conditions and forecast daily ice conditions. So far, however, little attention has been place to determine how good their forecasts are, or where improvements can best be made: winds, ocean currents or ice input data.

Research and operational models require offshore data from the atmosphere, ocean and ice-cover which is hard and expensive to obtain. Remote sensed data is the best data set available due to its availability and its large areal coverage. However, it needs to be verified by on-ice collected data. Neither reliable ice-cover property data such as ice and snow thicknesses, nor oceanographic data from beneath the ice cover will become available in the near future in spite of the large amount of effort. Forecast models need this data at least at weekly intervals for a few places of the total area to reach the expected accuracy in their prediction of ice-cover properties.

INTRODUCTION

Due to oil exploration in the ice-infested waters of Canada's Arctic and east coasts, the Panel of Energy Resources and Development (PERD) has sponsored ice modelling research to improve our knowledge of the ice-ocean processes for the safe management of the offshore activities. The ice modelling research supports the efforts by Ice Centre to improve their ice forecast models. The report by Nazarenko and Desrochers list details on the various ice-ocean models and will not be repeated in this short review. Another review paper on the subject was written by M. Ikeda (1989) and provides in detail some of the problems encountered by modellers doing research for the east coast of Canada This short review will follow the presentation of the workshop and discuss generally the following topics:

1. Environments of Beaufort Sea and the Labrador Sea
2. Cooperation in sea ice research
3. Types of Ice Models
4. Coupling of in ocean-ice-atmosphere models
5. Effects of the forecast period
6. Data requirements for research and forecast models
7. Future Research efforts at BIO

ENVIRONMENTS OF THE BEAUFORT SEA AND LABRADOR SEA

Research and operational ice models need to describe the ice conditions for two distinct geographical regions which differ significantly in environmental conditions and in the relative importance of ice parameters. A general model should not be used for both regions as the environmental conditions are different and the requirement of the offshore operator varies. The table below lists some of the differences of the environmental parameters occurring in the Beaufort Sea and the Labrador Sea:

	BEAUFORT	LABRADOR
Shelf Depth (m)	75	200-300
Offshore	cold source	heat source
Ice thickness	2m	1m
Floe size	large	small
Ice pressure	large	small
Ridges	6-10/km	none
Ice drift	small	20km/day
Shelf break current	10cm/s	50cm/s
Runoff	large	diluted

Table 1. Environmental Parameters of the Beaufort and Labrador Seas

Spatial scales and boundary conditions vary between the two regions which in turn will determine the magnitude of model parameters (ice rheology) and the treatment of boundary conditions. In addition the problems facing the offshore operator vary as well: so his requirement for ice information differs for the two regions (Table below).

	BEAUFORT	LABRADOR
Depth	50m?	100m
Ice	thickness/drift	drift
Ice forms	ridges	bergs
Others	pressure	waves
Latitude	Temp./Daylight	-----

Table 2. Offshore operational problems for the Beaufort and Labrador Seas

RESEARCH COOPERATION

Cooperation in sea ice model development and data exchange in Canada is streamlined by the PERD's Operational Ice Modelling Group chaired by D. Champ of ICEC. The group consists of researchers, forecasters, regulators and users and meets twice per year to discuss the cooperation project such as listed below:

1. DFO-CICE

- Ocean current data and model transfer
- ocean temperatures data (Gulf of St. Lawrence yearly ice cruise)
- ice-ocean coupled forecast model transfer
- ice-ocean process model results
- real time ice drift from satellite-tracked beacons
- ice drift maps from beacons and imagery
- ice model verification input (model, data and procedure)

2. DFO-NRC-CICE

- modelling ice ridge formation and pressure forces
- ice and ridge motions and thickness distributions
- ridge-ocean interaction processes
- modelling and ice pressure by satellite tracked beacons

3. CCRS-DFO-CICE

- SAR data for ice modelling
- SAR data for ERS-1 ice data verification
- ice thickness data to verify SAR algorithms

Other cooperation exists between users (Coast Guard, Can Petrol. Assoc. and COGLA) as well as other research institutes, universities and consulting companies (a partial BIO's list):

C-CORE	- ice growth instrumentation for modelling
ASA/Arctic Sciences	- ocean, ice modelling
Memorial University	- ocean modelling
McGill University	- ocean/ice climate modelling

TYPES OF RESEARCH AND OPERATIONAL ICE MODELS

Ice models are characterized (type, by their spatial coverage. A one-dimensional model describes the ocean-ice-atmosphere coupling process in the vertical direction only. The model type, however, does not specify the coupling process being modelled (dynamic, thermodynamic or buoyancy driven) and as such only provides part of the information needed to determine what the model can and can not do. Some of the existing models in use can be characterized by this description, other models describe one specific process and are usually referred to as process models:

I. One-dimensional Models

- Freezing-Degree Day models
- Ocean mixed layer models

II. Two-dimensional Models

- Barotropic ocean models
- ice growth/decay models

III. Three-dimensional Models

- Baroclinic ocean models
- ice ridge formation models

IV. Process Models

- Ridge keel-ocean interaction
- Ekman Divergence/currents at ice edge
- Upwelling/melting at the ice edge
- Long wave generation at the ice edge
- Cross shelf ocean and ice eddy fluxes
- Topographic steering of currents
- Topographic generating of eddies

All of the research models are continually being updated as better data and calibration coefficient become available. Even the simplest one-dimensional Freezing-Degree day models are being updated.

SEA ICE AND OCEAN MODELLING RELEVANT TO THE LABRADOR AND NEWFOUNDLAND SHELVES

Since a large portion of modelling work supported by PERD has been carried out for the Labrador and Newfoundland shelves, the detailed review in Ikeda (1989) on modelling relevant to the shelves, including both sea ice and ocean models, is summarized here.

Various numerical models used for individual process studies included the following processes: growth and decay of sea ice, ice advection, oceanic mixed layer development, wind-driven shelf circulation, topographic effects on ocean currents over the continental shelf and slope, and mesoscale eddies. Each one of these models had some of the processes. The process studies based on those models suggested the future direction of model development, which is now undertaken at BIO. A model to address seasonal ice advance and retreat will have the following features: vertical stratification, which controls convective overturning, and realistic bottom topography, which regulates ocean current, particularly over the shelves. To reproduce a seasonal cycle of ocean circulation, sea ice will be included because the coupling between sea ice and ocean can be important both dynamically and thermodynamically. In addition to this model development, model verification will be made with historical data of oceanic structures and sea ice.

In terms of short-term variability, individual physical mechanisms (ice advection, shallow oceanic mixed layer under melting ice, wind-driven shelf circulation, mesoscale eddies) have been studied extensively so that simulation may be attempted in the near future. Mesoscale eddies were predicted for a couple of weeks using a quasi-geostrophic (QG) eddy-resolving model. Ice melting were correctly calculated using a mixed layer model. Hence, combination of these two models may be able to forecast ice movement and melting over the shelf and in the marginal ice zone. Wind-driven circulation over the shelf were reproduced by a barotropic ocean model, with which an ice model were coupled. This coupled model is now under verification with the observed data at AES, Ice Centre. The further examination is required for mesoscale variability over the steep slope, for which the QG model is not valid. Primitive equation models available in the oceanographic community will be tested with each other as well as the QG model. Assimilation techniques to be developed in the other PERD projects are expected to play significant roles in the verification.

ICE-OCEAN-ATMOSPHERE COUPLING

Although all ice forecast models couple the ocean, ice and atmosphere, the degree of coupling (what process) and the direction of the coupling vary greatly between models. This causes a lot of confusion as all models claim to couple the ice cover to the atmosphere and/or ocean. The coupling process can be:

1. DYNAMIC coupling using drag coefficients for the wind and water stresses.

2. THERMODYNAMIC coupling using eddy coefficients for sensible heat, latent heats of evaporation and fusion and heat conduction coefficients.

3. BUOYANCY generated coupling from evaporation, sublimation, melting, brine rejection...

The coupling processes listed above do not occur in isolation but influence each other. For instance, the buoyancy fluxes do affect oceanic pressure gradients which generate currents. These in turn redistribute the pack ice, altering buoyancy fluxes, thus starting a second turn around the iteration loop.

Specifying the coupling process between two media by the above terms alone will still not describe the details of the model. One also has to know if the coupling occurs in both directions or is one medium prescribed (used as a boundary condition) and is not affected by the other medium. This is always done with the atmosphere-ice cover coupling; the atmosphere affects the ice cover but the ice cover does not affect the atmospheric conditions. The coupling is thus only in one direction and does not describe completely the total coupling process. Models vary in their

handling of the coupling process of the atmosphere and ice cover/ocean by either being:

1. unidirectional such as in Freezing-degree Day and mixed layer models

2. bidirectional (some surface conditions fixed to climatic means)

3. interactive (all surface conditions free to adjust)

Most models use eddy coefficients in their coupling processes, but this is an approximation to the three dimensional fine scale turbulent coupling process. Eddy coefficients approximate turbulent processes to time-averaged gradients of the medium being described:

$$(w'T') = A_z dT/dz$$

The turbulent process described by (w'T') is averaged over time and related to a mean temperature gradient dT/dz by the eddy coefficient A_z. Only turbulent closure models describe the turbulent coupling process by model derived parameters and study how the eddy coefficients vary as the derived parameters.

FORECAST PERIOD

The forecast period has been extended from days to weeks in operational models and to years in research models (hindcast mode). The forecast period can affect the assumptions (approximations) used by a model. The forecast period determines what forcing parameters can be ignored or approximated.

1. Short period forecast.

in an 1-2 day ice drift forecast a constant ocean ice drift is a good approximation and thermodynamics can be ignored. However, for an ice edge model oceanic melting can not be ignored even for an 1-2 day forecast. Models with specific tasks vary in their approximations of ice/ocean coupling parameters and each one may very their handling of the parameters the longer the forecast period becomes.

2. Hindcast and forecast.

Most research models claim to be forecasting but in reality they used the data first in a hindcast mode before they forecast. In the hindcast mode they know what the answer is and thus will achieve this. They use the data to calibrate model parameters before they forecast. On the other hand, operational models truly forecast and use predicted boundary conditions (atmospheric parameters). When data becomes available, it is used to initiate model boundary conditions to improve the forecast.

3. Real-time data.

Real-time data is required to update boundary and initial conditions in operational models. This will improve the quality of their forecast. Presently a large component of PERD's projects at BIO is spent on methods to include real-time data into research models and to obtain real-time oceanographic and ice data from ice-infested waters.

DATA REQUIREMENT

1. Forecast models

Real-time ocean parameters from at least a few grids in the domain of the forecast area are required at weekly time intervals. Although this is a simple statement, it is very difficult to achieve. The technology to send data back by a buoy that can survive the ramming and submerging by ice floes is being developed but has not been field tested.

Real-time ice data is presently available through remote sensing technology and more ice data will become available through SAR-borne satellites. However, SAR data is not a direct measurement of the ice thicknesses, but inferred. Calibration data from on-ice measurements or other easily calibrated techniques (Electromagnetic/Radar) is required to calibrate the algorithms used for remote sensed data.

2. Research models

Research models require data to increase our knowledge of the ocean-ice-atmosphere coupling processes. Current studies sponsored by PERD are collecting data to increase our ability to model these processes. Some of the processes being looked at are:

ice ridge formation
ridge keel-ocean interaction
ice edge melting/upwelling
cross-shelf eddy fluxes
ice pressure affects on ice drift
topographic steering/eddy generation

3. Calibration of constants

Models use a lot of constants that approximate fine scale turbulent processes to time-averaged mean parameters. Now these constants are being varied in models to fit observations. A better understanding of the magnitude range of these constants and the reason for their variability is required. Then comparison of results from models with different physical approximations can be done without the worry that differences are caused by the choice of the value of the constants. Some of the least known constants are:

Eddy coefficients for marginal ice zone
Drag coefficients for marginal ice zone
Thermal Ice constant due to Salinity/Temperature effects

CONCLUSION

This short review on research and development of sea ice modelling showed that:

1. Beaufort and Labrador Sea environments are different and models should treat them differently.

2. All models are continually being updated.

3. Process models improve our understanding and are required as part of our aim to

improve operational forecast models.

4. Meaning of "coupling" in model types (1- to 3-D) varies greatly and should be clearly stated as to what process and how interactive the process is modelled.

5. Forecast period affects model approximations.

6. Present efforts at BIO are directed to:

   - 3-D ocean/ice model
   - process models/data
   - real-time data assimilation
   - real-time data acquisition

REFERENCES

Ikeda, M., 1989. A review of sea ice and ocean modelling relevant to the Labrador and Newfoundland Shelves. IEEE transactions on Geoscience and Remote Sensing. Vol. 27(5): 535-540.

Nazarenko, D. and D. Desrochers, 1991. A state of the art review of sea ice modelling. Part of this proceedings.

SUMMARY OF LEARNINGS AND RECOMMENDATIONS

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Calgary, AB

Before discussing learnings and recommendations, it is appropriate to first reflect on what is an "ice model" in the context of the PERD mandate. Figure 1 attempts to do this. Ice models can be thought of as predictive tools which either allow calculation of design ice loads or a forecast of ice conditions. There is some similarity between these two kinds of models in the context of ingredients. For example, the general characteristics of an ice load model are given in Table 1 and further elaborated in Figure 2. Ice load models are not the subject of this workshop, therefore further discussion is not warranted but the linkages to ice forecast models should be noted.

An ice forecast model has the characteristics defined in Figure 1 and will generally be aimed at providing answers to

- Where is the ice?
- What is its concentration?
- What is the ice type?
- How thick/large is the ice?
- How quickly is it moving and in what direction?
- When will it reach a given location?

During the course of this workshop, ice forecast models have been discussed in the context of the user's needs, the types of models used, the deficiencies, and future needs. The learnings and recommendations are summarized in point form below.

LEARNINGS

- Forecasting needs will vary with type of operation and area (see B. Wright's presentation).

- Importance of various "physics inputs" will depend on area, time or year, time-scales, ice types, etc. (see S. Prinsenberg's presentation).

- Strategic (e.g. longer range) predictions are unlikely to be used in a forecast mode unless uncertainties are negligible (e.g. initiating or cancelling a $50M drilling operation).

- However, such models may be useful in a statistical mode, in a planning context, to assess risks of failure or success.

- Some physics inputs not well understood (e.g. ice rheology).

- But biggest deficiency in developing/applying comprehensive ice forecast model in inability to provide input drivers (e.g. winds, currents).

- Wind is a major driver. If ability to predict winds is limited (say to 24/36 hrs), then is this the limit of the ice modelling time-scale?

- Ice models need to be verified/tested.

- Simplified tactical models are desirable and may work 9 out of 10 times.
- Can we anticipate when they don't work?

RECOMMENDATIONS

- Ice modelling should be integrated with ice detection/remote sensing and ice management into a total forecast system.
- Ice detection/remote sensing will continue to improve.
- RADARSAT will soon provide all-weather images of ice at a maximum interval of 72 hours.
- Also marine radars and ground wave radars are improving.
- Therefore, a tactical ice model may only need to be good to 24/72 hours and to within 20-50 km spatially.
- The simplest, most reliable model to achieve this should be striven for.
- Working Group on ice forecasting should continue its work (see Logic Diagram - Figure 3)
- User presence should be strengthened (e.g. Coast Guard; Canarctic; ?)
- Recommendations from the Working Group should form the PERD strategies and work plan.

In the mean time:

- Research to allow effective assimilation of remote sensing/detection data into a coupled detection/forecast operational model should be strengthened.
- Research to assess when simple forecast models won't work should continue (but not dominate the effort).
- Impacts of long term trends, such as climate change should be recognized but not overworked.

TABLE 1

ICE LOAD MODELS

INPUTS

- Ice conditions scenarios (winter, break-up, summer, ice types)
- Ice thickness distributions
- Arrival rates of ice features (e.g. (icebergs)
- Floe sizes; ice morphology
- Ice failure stresses/pressures
- Driving forces

APPROACH (SEE C.S.A. LOGIC) *

- Simulation of extremes based on ranges of values of the inputs expected during the lifetime of the structure
- Apply a factor of safety to cover uncertainties

NOTE

- Distributions of inputs best obtained by measurements and observations rather than by modelling from 1st principles.

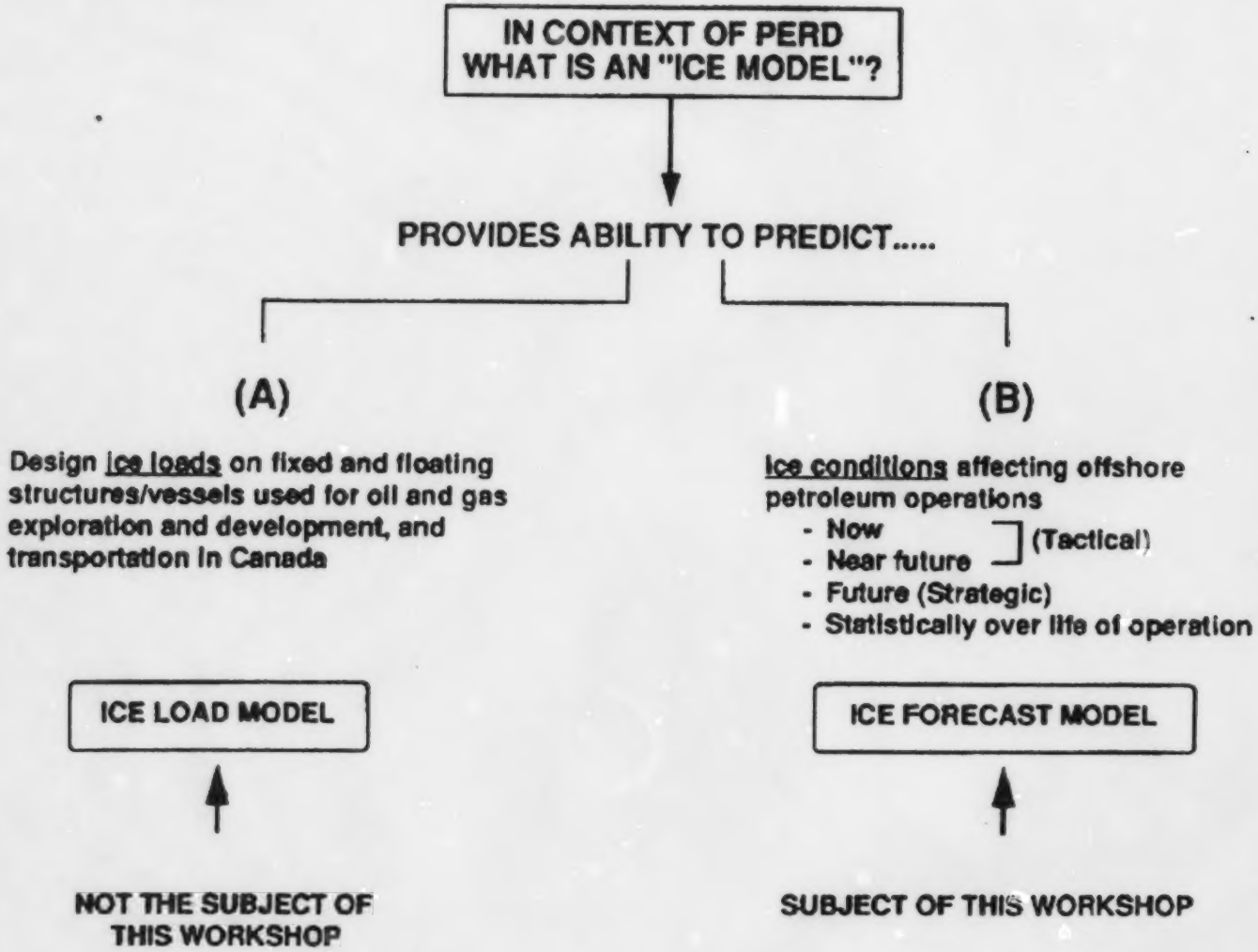

IN CONTEXT OF PERD
WHAT IS AN "ICE MODEL"?
PROVIDES ABILITY TO PREDICT.....
(A)
Design ice loads on fixed and floating structures/vessels used for oil and gas exploration and development, and transportation in Canada
ICE LOAD MODEL
NOT THE SUBJECT OF THIS WORKSHOP
(B)
Ice conditions affecting offshore petroleum operations
- Now
- Near future
(Tactical)
- Future (Strategic)
- Statistically over life of operation
ICE FORECAST MODEL
SUBJECT OF THIS WORKSHOP

FIGURE 1

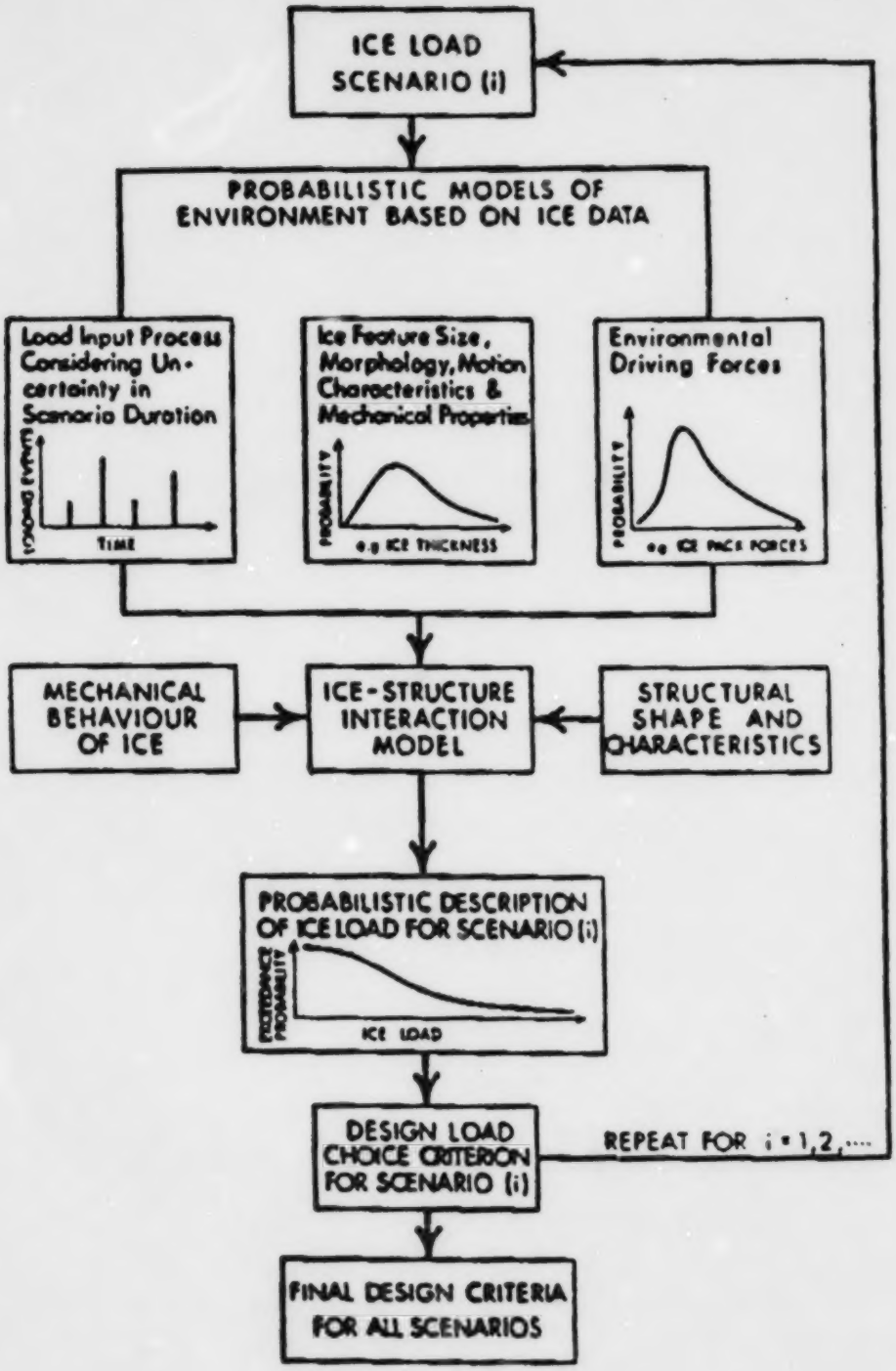
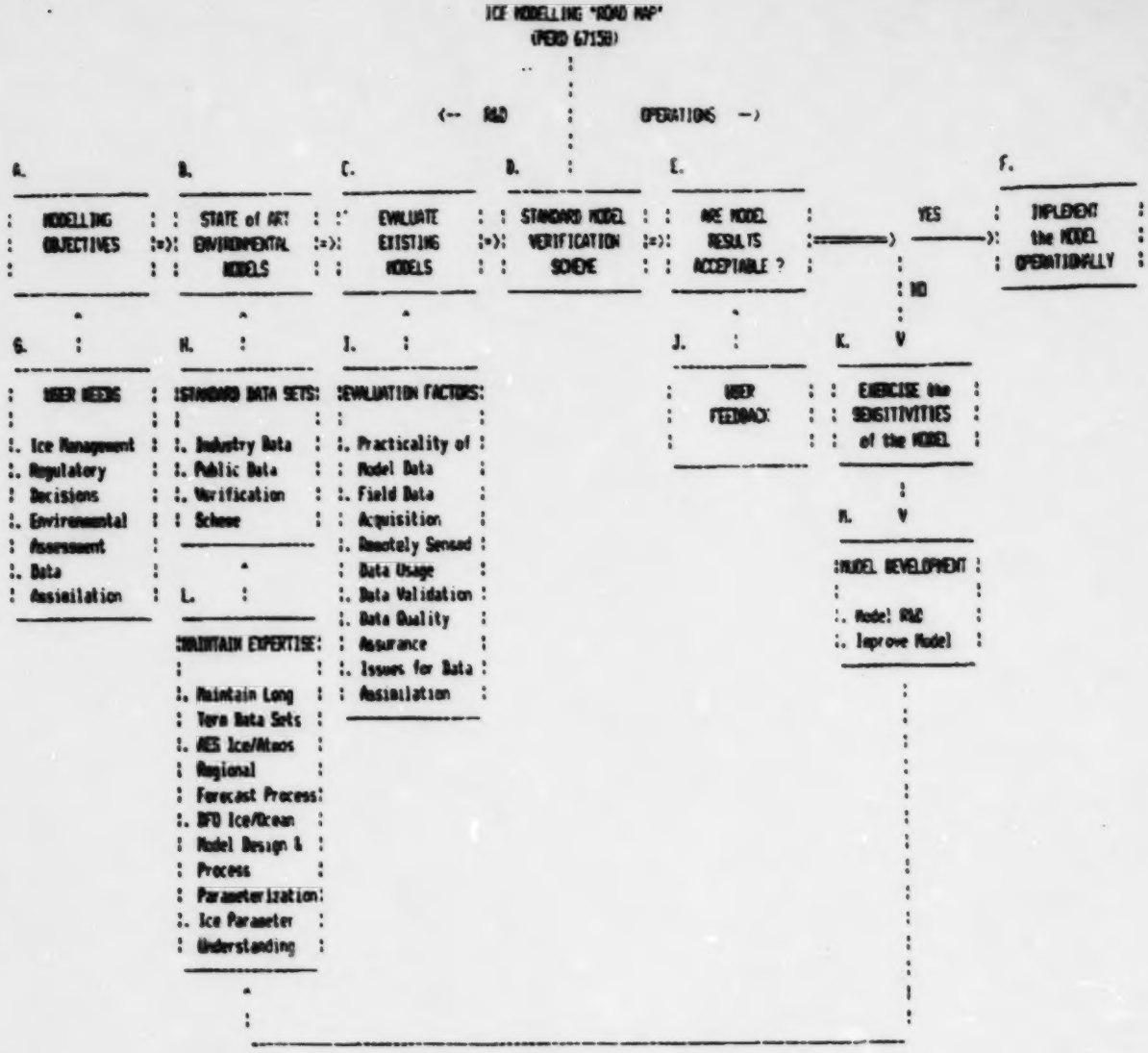


FIGURE 1.

Overall Approach



B.I.O. Projects	Letter	I.O.S. Projects	Letter	AES Projects	Letter
67119 Ice-Water Instr.	I.	67113	I.	67156 Sea ice modelling	A,B,C,D,E,L,M.
67139 Ocean Curr (Sat A)	I.	67114	B,I.		
67162 Sea Ice Flux Mfld	B,C,M,I,M.	67160	I.		
67165 I Shelf M/Ice (C2)	B,C,I,M.	62334	I.		
67166 RV/ST Ice Prod	B,C,I,M.	62335	I.		
67173 Verify Sat Oc Data	C,I.	62343	I.		
67177 E Can Clim&Sea Ice	B,C,M.				
67178 Assim data -Ice/Oc	C,I.				
67NEW Assim data -Waves	C,I.				
62139 Waves in Ice Mods	C,I,M.				
62225 Grndbnks Ice Study	C,I,M.				
62342 E/M Ice Sounding	C,I,M.				
62345 Sealce Properties	C,I,M.				
62NEW Ice Pressure	C,I,M.				

FIGURE 3

WAVE MODELLING

Chairman: Ron Wilson, Marine Environmental Data Service

Rapporteur: Val Swail, Atmospheric Environment Service

SUMMARY
RESEARCH, DEVELOPMENT AND OPERATIONAL USE OF WAVE MODELS

A review was made of oil spill trajectory models, current models, and wave models to provide a synopsis of present capabilities in Canada. The review focused on operational needs, the present status of operationally-oriented models, ongoing and planned research and linkages between the operational, development and research communities.

The review provides general information on model components and expected performance; it was not intended to provide detailed technical specification concerning model parameterization or physics. The important components of the models were reviewed for the purpose of providing an overall indication of capabilities, rather than to provide a basis for selecting operational models for given applications.

The purpose of the review was to serve as a discussion paper. It is anticipated that it will be used by interested parties to develop their own recommendations pertaining to future research and model development.

Reference: Godon, A., D. McGillivray and D. Dickins. 1991. Status: Research, Development and Operational Use of Ocean Models. Prepared for the Panel on Energy Research and Development by D.F. Dickins Associates Ltd. and the MEP Company Ltd.

BACKGROUND

The Panel on Energy Research and Development (PERD) undertook a study to evaluate the direction of research efforts required to provide effective oil spill trajectory, current and wave models for operational use. The following sections summarize the results of the current model review. Further detail is available in Godon *et al*, (1991) which is included as an Annex to these proceedings.

While the review was intended to be comprehensive, it was acknowledged at the outset that time and budget considerations would potentially constrain this objective. However, it was felt that the results would provide a useful foundation upon which to build during the Workshop. At that time, comments and additions were solicited from Workshop participants. These have been compiled and follow the summary.

The review included an examination of communications linkages between researchers, developers, operators and users of models. The objective of this aspect of the review was to identify deficiencies in existing linkages in order to improve future mechanisms whereby research efforts can lead to more effective operational products.

For the purposes of the review, an "operational model" was defined as a numerical prediction system which processes forecast or observed inputs to compute output forecast products such as wave spectra. Models which were considered potentially operational were defined as "operationally-oriented". To be classified in this manner, a model would not presently be in regular use, but would have been designed and tested to run in a realistic operational setting.

WAVE MODELS

The review identified the Atmospheric Environment Service (AES) as the principal user of wave models in Canada. It is involved in all aspects of wave modelling from research through operations,

providing wave forecasts for mariners in Canadian waters.

Although the level of offshore activity is low at this time, the oil and gas industry has also been directly involved in development and application of wave models. The industry uses wave forecasts directly, and normally employs contractors to operate the models and provide forecasts. Private contractors typically use purchased models, sometimes incorporating in-house modifications. Table 1 summarizes needs of the oil and gas industry identified in a recent Environmental Studies Research Funds project (Hodgins and Hodgins, 1988).

Table 1
Desired Wave Forecast Requirements for Offshore Oil and Gas Drilling Operations (after Hodgins and Hodgins, 1988)

Parameter		Precision	Accuracy
Wind Sea	- Significant height	0.3 m	± 8%
	- Significant period	1 s	± 10%
Swell	- Significant height	0.3 m	± 8%
	- Period	1 s	± 10%
	- Direction	8 pts compass	± 20%
Combined Sea	- Significant height	0.3 m	± 8%
	- Period	1 s	± 10%
	- Maximum height	0.3 m	± 8%
Spectrum	- One-dimensional	15 frequency bands	4*RMSE within 15%

Note: all parameters were desired for 12 hrs at 1 hr intervals and from 12-48 hrs at 6 hr intervals.

WAVE MODEL CHARACTERISTICS

Wave models can be classified as being parametric wave height, parametric spectral, or discrete spectral models. Parametric wave height models predict monochromatic expression of wave height and period based on fetch and wind duration. Parametric spectral models solve the conservation of energy equation as a function of time and use the result to compute the change in energy at a specified point of interest with wave energy presented as a frequency spectrum. Discrete spectral models describe the two-dimensional spectrum in terms of a finite set of frequencies and directions.

WAVE MODELS REVIEWED

Five Canadian operationally-oriented wave models were reviewed; four parametric spectral models and one discrete spectral model. Table 2 summarizes key model particulars.

The Ocean Data Gathering Program (ODGP), developed by Oceanweather, Inc. is the source model

for the AES Canadian Spectral Ocean Wave Model (CSOWM) and the Pacific Wave Model (PACWAV). A third version of ODGP has recently been installed in METOC for operational use along the Atlantic Coast.

Two other discrete spectral models WAVAD, developed by D. Resio and SPECREF, developed by Seaconsult Marine Research Ltd. are both being operated in Canada on a commercial basis, the former by Oceanroutes (Canada) Inc. on the East Coast and the latter as part of Seaconsult's Seaweather System for B.C. coastal waters.

Table 2
Summary of Canadian Operationally-Oriented Wave Models

Model	Primary Purpose	Input Data	Model Type	Limitations	Configuration	Output
CSOWM	CMC and METOC forecast for East Coast	*CMC gridded wind fields	1G spectral model	shallow water effects, CMC winds used as is, out of grid swell	CMC CRAY XMP	4 panel map of sig. wave height & period, swell, direction
Donelan's model	forecasts for Ontario Weather Centre	marine wind forecasts	parametric spectral model	shallow water effects	CMC CRAY XMP	sea state at specific locations
PACWAV (MacLaren Plansearch, Cardone)	Pacific Weather Centre forecasts	CMC isobaric field, local observations, Ta, Ts	1G spectral model	shallow water effects, out of grid swell	HP 9000 workstation mouse	sea state, spectral energy, swell
SPECREF Seaconsult	forecasts B.C. coast	CMC/surface wind forecasts	decoupled propagation model	site specific	PC with 2400 baud line communicatio ns	refraction diagrams
WAVAD (Don Resio)	hindcasts forecasts by Oceanroutes	gridded wind field data	2G coupled discrete model	no wave-current interaction or wave diffraction and reflection	IBM 386	sea state at site

Notes: 1G,2G - first generation, second generation
*different inputs are used for the east coast (CMC finite element model 10 m winds) and the west coast (CMC spectral model 1000 millibar winds

The final operational wave model reviewed is a parametric spectral model developed by M. Donelan of the Canada Centre for Inland Waters (CCIW). The model is run operationally by the Ontario Weather Centre for selected sites in the Great Lakes. The model has particular application to fetch-limited water bodies and has recently been tested for operational use in the Beaufort Sea.

WAVE MODEL RESEARCH

The National Waves Committee (NWC) is an ad hoc group which seeks to coordinate research efforts and ensure links between research, industry and government organizations in Canada. Canada also participates in the Wave Modelling Group (WAM) which provides a similar function to NWC but on an international scale.

Canadian wave model research is being conducted by AES, the National Water Research Institute at CCIW, and the Institute of Ocean Sciences (IOS) and Bedford Institute of Oceanography (BIO), both part of Fisheries and Oceans Canada. Some important research efforts include the following:

S. Clodman, AES	Refinement of parametric wind wave models
M. Khandekar, AES	Computational performance for CSOWM; AES representative to WAM group
M. Donelan, CCIW	Participation in the multi-national Surface Wave Dynamics Experiment (SWADE)
D. Masson, IOS	Wave-Current interaction
W. Perrie, BIO	Remote sensing data assimilation; wind-wave coupling
F. Dobson, BIO	Sea surface drag
S. Smith, BIO	Air-sea momentum flux

OPERATIONAL/RESEARCH LINKAGES

Linkages between operations and research groups were studied with an interest in identifying areas where the operational utility of models could be enhanced through improved communications, or better information transfer. Through the review, it was found that while linkages could be identified between researchers, model developers, model operators and users of model output, the strength of these linkages varied.

Within the wave modelling community clearly defined linkages between researchers and developers are few because both functions tend to be performed within a given wave modelling group. An exception to this is the NWC which provides a forum for information exchange between researchers, developers, operators and users. As noted before, Canada's participation in WAM provides an important link to the international wave modelling community. In all cases DFO and AES provide a focal point for communication between the various interest groups.

WORKSHOP RESPONSE TO THE OCEAN MODEL REVIEW
WAVE MODELLING COMPONENT

A review of operational and research ocean models was prepared for PERD (Status: Research, Development and Operational Use of Ocean Models by D.F. Dickins and the MEP Company) for distribution and comment at this Workshop. While the full review is attached as an appendix to these proceedings, comments from Workshop participants pertaining to the review are noted here.

COMMENTS CONCERNING THE STATE OF THE ART REVIEW

p. B-iii — The WAM model is available for both research and operational purposes from K. Hasselmann at Max Planck Institute, Hamburg, Germany. The model is presently being used at both BIO and IOS for research and development purposes.

p. B-36 — It was noted that the Department of National Defense is an important user of operational wave models and also serves as an operator of wave models through the METOC centres.

p. B-37 — While the review document suggested that mariners did not require the same level of wave forecast information as the offshore oil and gas industry, it was pointed out that mariners, including fishermen, container fleets and the navy require storm wave warnings 36 hours in advance.

p. B-39 — It was noted that the third generation terms in ODGP, developed by Cardone, are essentially WAM model terms. WAM should therefore also be considered an operationally-oriented model as it has been adapted for operational use in Canada.

p. B-42 — The suggestion that models are "competing with simple wave nomograms" was disputed. Documented comparisons (SWAMP Group, 1985 as referenced in the review) clearly demonstrate the superiority of models.

p. B-48 — Additional wave modelling research is being conducted at BIO beyond what is described in the review document.

The wind-wave coupling work of W. Perrie includes investigations where a boundary layer model in operation at RPN in Dorval was coupled to a wave model to investigate the effects of boundary layer parameterization on wave energy and significant wave height. Other work by Perrie and B. Toulany (BIO) involves comparisons between winds measured in situ with those wave slope measurements to permit parameterization of wind speed in terms of spectral wave slope energy.

Perrie and Toulany, with D. Mercer (Dalhousie University) have also recently undertaken investigations to assimilate GEOSAT remotely sensed wind speeds and wave height information into wave models and their input wind fields to evaluate the effect of on wave model forecasts.

Perrie is also studying wave-ice interaction.

In conjunction with the ERS-1 work noted, F. Dobson is Scientific Authority for a

three year, RDDP-funded program to incorporate algorithms developed by S. and K. Hasselmann to permit SAR data assimilation into the ODGP wave model.

The noted field work to ground truth ERS-1 data has an equally important objective to study wind-wave coupling.

The air-sea flux research of S. Smith entails investigation of momentum, heat and water vapour flux.

p. B-59 In describing linkages between researchers and developers of wave models, the role of DFO researchers is left unclear. Investigators at BIO (W. Perrie), IOS (D. Masson), and CCIW (M. Donelan) interact with researchers at AES as well as outside contractors as part of the research process. Both AES and DFO scientists also interact with outside contractors to direct the development process of wave models.

p. B-59 DFO involvement on the National Wave Committee includes representation from CCIW.

In addition to M. Khandekar, W. Perrie, D. Masson and M. Donelan are involved in WAM, participating in advanced model research.

p. B-61 An important linkage exists between AES and DFO research groups and private consulting firms involved in the operation of wave models. Research personnel regularly interact with these users, providing technical expertise on a consultative basis to firms such as MacLaren-Plansearch, Seaconsult, Oceanroutes, etc.

p. B-61 It was noted that all models need good wind stress information. Key work in this area relating the coupling of the wind to the water is being conducted by the wave modelling community. On this issue, linkages between modelling communities offer potential benefits of wider interest than simply those related to wave modelling.

Related to the point above, all Canadian research on the specification of the wind fields themselves is being done within the wave modelling community.

Important research is also being conducted at BIO on current-induced waves.

p. B-65 The 3G WAM model is being used operationally at ECMWF and is available for use in Canada, through W. Perrie.

p. B-66 In assessing the relationship of wave models to oil spill trajectory models, it was noted that wave models can provide important information from which to better estimate the coupling of wind to surface currents.

With reference to the last sentence, W. Perrie is presently developing a model to estimate wave-induced currents.

WAVE MODELLING - ONE USERS' PERSPECTIVE

(Abstract Only)

F.J. Dello Stritto, D. Szabo, & E.P. Berek
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Dallas, Texas

Numerical wave hindcast models are a key technology in the offshore industry. Their development over the last quarter century is a true success story of cooperation among the research, government and industry technical communities. In the design, analysis and reassessment of offshore facilities, they are a basic tool in establishing extreme wave criteria, which are critical for many applications. For engineering applications, the most important area for advancement is modelling in shallow waters and complex bathymetrics.

Since measured wave records of sufficient length exist for very few sites, and since continuous hindcasts over very long periods is not practical, extreme wave criteria are often developed by the following five steps:

- Identification of Severe Storms
- Hindcast Modelling of the Storm Seastates
- Verification of Hindcast Results with Measured Data
- Extremal Analysis
- Analyses for Engineering Parameters

Wave modelling was commonly viewed, not too long ago, as the weak link in this chain. For many offshore areas, they are no longer, due to the sustained development and improvement of the models, and perhaps more importantly, to increased attention to accurate description of the wind fields. However, the fact that verification of model results with measured data remains a key step in the process, indicates less than complete trust in the models.

Use of wave models in developing extreme criteria can boast some recent, well-known successes. Among these are NESS (North European Storm Study), GUMSHOE (Gulf of Mexico Shallow Water Hindcast of Extreme), WAX (West Africa Extreme Waves Study) and the Wind/Wave Hindcast Extremes for the East Coast of Canada Studies. An overview of these studies raises the following concerns which should be addressed in future development:

1) As stated above, wave model performance in shallow water (ie. in water depths where bottom effects significantly influence the wave fields) is not adequate for many engineering applications.

2) Most verifications are, of course, performed with measured data from seastates far less severe than the extremes of interest. Comparisons with the limited data from extreme seastates have not been completely satisfactory. (Note: the measured data, especially in high seastates, are often suspect themselves)

3) Again, based on comparisons with limited and sometimes suspect data, models underestimate the peak seastates in severe storms too often. (Note: This underestimation is less frequent than sometimes described. Model results are 1 to 3 hour averages of significant wave height. Raw measured data usually are 20-minute averages (whose peak values must be higher). Valid comparisons must be

based on comparable time averages).

In summary, numerical wave models are indispensable tools of the offshore industry. Their development over the past quarter century is a true success. Further development in their performance in shallow water, and further verification, especially for severe seastates, is warranted.

REGULATORY REQUIREMENT FOR OCEAN WAVE MODELS

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The mandate for the offshore regulatory responsibilities of the National Energy Board (NEB) arises from a number of Acts including the Oil and Gas Production and Conservation Act, the Arctic Waters Pollution Prevention Act, and the Environmental Assessment Review Guidelines Order. These responsibilities encompass ensuring the safety of personnel and of oil and gas operations from the environment and protection of the environment from the operations.

A number of means are available to the NEB to discharge these responsibilities. Prior to commencement of any offshore activity, the Environmental Assessment Review and the Regulatory Approvals processes are used. Once an activity is under-way, inspections and monitoring provide the means. Upon completion of an activity a post completion review is utilized. NEB also initiates, supports, and manages R&D relevant to the development of an equitable regulatory regime and more efficient, environmentally safe operating procedures.

SAFETY OF PERSONNEL AND OF OPERATIONS

ENVIRONMENTAL DESIGN CRITERIA

During environmental assessment and regulatory review of a proposed offshore exploration, development or production activity, the regulator must be satisfied that the structures or equipment proposed for the activity is appropriate for the maximum environmental loads and conditions that may be experienced in the region of operation. Environmental Design Criteria (maximum loads) as defined by accepted standard-code setting organizations such as Canadian Standards Association (CSA) or the International Maritime Organizations (IMO) are generally consulted to determine the suitability of the structure. A Certificate of Fitness issued by a Certifying Authority is required. The regulator is responsible for ensuring that appropriate environmental design criteria are applied.

In harsh northern environments, wave loads are second only to ice loads in magnitude of the forces that may experienced by an offshore structure. Thus, wave design criteria or the design waves (usually defined in terms of maximum significant wave height and period) are critical parameters for offshore structures. The design wave for an area of operation is generally given in terms of probability of occurrence (return period) and is developed through a statistical examination of a wave data record of appropriate duration. Unfortunately, for many areas of the Canadian offshore, records of acceptable duration and temporal-spatial distribution are not available. Existing data records must be supplemented by hindcast data from wave models. Once model data are validated, they are often preferred to observed data in that they are internally consistent and may be created to be both spatially and temporally comprehensive for any proposed area .

OPERATIONAL LIMITS

The suitability of a structure or supporting equipment for a proposed offshore operation is derived from consideration of the response of the structure or equipment to wave conditions (wave climate) in the area of operations. If the operational limits of the structure or equipment are expected to be exceeded frequently or for periods of significant duration, the structure or equipment may not be suitable for the area either in terms of safety or efficiency. Again, wave

data records are often insufficient to define the wave climate. They may need to be supplemented by hindcast data from wave models.

OPERATIONAL SUPPORT

Once a structure (equipment) with a given set of operational limits is approved for an activity or region, the regulator may require that wave models be available for operational support. Reliable prediction of operationally limiting sea states with a 6-12 hours advance notice would provide a significant contribution to the safety of personnel and operations. The more sensitive an operation (drilling, emergency response, search and rescue) is to sea states the more significant the impact of reliable prediction. Further, the longer the shutdown time required to safely wind down a given operation, the more significant the value of the advance warning. Wave models may also be useful for operational planning of activities such as ice/iceberg management and operation of loading or personnel transfer equipment.

PROTECTION OF THE ENVIRONMENT

OPERATIONAL LIMITS

Structures or equipment with operational limits that are too low for the proposed area of operations may pose a threat to the environment by raising the probability that the limits may be exceeded without sufficient advance warning. In the selection of equipment and structures to minimize risk, wave models may be required to provide supplemental data to define expected wave duration and exceedence statistics for an area.

EMERGENCY COUNTERMEASURES

Wave model support may be required for two purposes. First, at the planning stage, to define the expected wave conditions for the area of operations in order to determine suitability of countermeasures plans and equipment. Second, at the operational stage, to provide support in the planning of the response, and the deployment and operation of countermeasures equipment.

REGULATORY PERSPECTIVE ON WAVE MODELLING R&D REQUIREMENTS

In support of the environmental assessment and regulatory approval processes for oil and gas activities in the offshore further work in wave modelling is required to address the following:

- model validation methodology and data bases for evaluating new models and model performance
- data assimilation (real time and research mode) from remote sensing platforms
- reliable operational models providing accurate forecasts with significant advance warning to encourage user acceptability
- wave/current interaction
- wave/ice interaction
- shallow water effects

- subsea erosion and scour
- wave breaking forces on structures
- wave rideup on berms and artificial islands

WAVE HEIGHT FORECASTING AT METOC HALIFAX

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ABSTRACT

METOC Halifax provides routine wave height forecasts to the marine and military communities. These products are prepared under the pressure of rigid deadlines and depend ultimately on subjective analyses of wind- and wave-fields. In turn, these analyses depend largely on reports from ships of opportunity. Unfortunately, such reports are irregular, inconsistent, sparse, and sometimes unreliable.

Remote sensing from satellites will provide regular, consistent, and reliable data over wide areas. When this potential is realized, analyses could be significantly improved. Wave models already provide guidance with which forecasts could be improved. Unfortunately, incorporating these new products into METOC's wave forecasting program remains a problem.

Specific problems include:

- incorporating asynoptic data into synoptic analyses;
- getting these data to the forecaster in real time and in a convenient format; and
- making model output available to the forecaster in a convenient format and at a time when guidance is useful.

METOC looks to the research community for solutions to these problems.

HISTORICAL BACKGROUND

In the early 1960s METOC began producing routine wave height forecasts. Since then METOC has produced wave analyses every six hours and forecasts every 12 hours. The analyses for 06Z and 18Z are used internally. The ones for 00Z and 12Z are transmitted to users along with the forecasts. The forecasts extend to 36 hours. Analyses are archived indefinitely while forecasts are archived for one year.

Until recently, METOC was the only organization in this country to have such a program. As a result, many of the most experienced Canadians in operational wave forecasting either are still at METOC, or got their training at METOC. In the 1970s, an upsurge in offshore exploration led to government policies which stimulated private-sector forecasting of weather and waves. In the 1980s, as a result of the LeBlond Commission, AES established Marine Specialist positions in public weather centres on both coasts. These specialists were expected to provide the marine community with better service in general, and wave forecasts in particular. The techniques used by these Marine Specialists for wave forecasting are based largely on those used or developed at METOC.

The operational procedures used at METOC are based on ones developed in-house by Dick Morgan in the late 1960s and early 1970s. They were based on locally- produced wind forecasts

and depended on nomograms published by Suthons in 1945 and Bretschneider in 1953. They have worked very well in an operational setting and have changed only a little since then.

A few years ago, Canada's first operational wave model, the Parametric, became available to forecasters as guidance. But it earned little or no respect in the field among experienced forecasters. Its replacement, the Spectral Ocean Wave Model, was introduced a few months ago, and is regarded at METOC as a significant improvement.

Graphical workstations are now being introduced, and within the next few months we expect forecasters to learn to do on a screen much of what they now do on paper.

OPERATIONAL PROCEDURES

The first step in the process is to produce a T0 Wave Analysis. The isopleths on this map are of Combined Height, which is calculated from

$$H^2 = H_1^2 + H_2^2 + H_3^2$$

where H_1 is the height of the wind wave, and H_2 and H_3 are the heights of swell waves.

The next step is to prepare wave forecasts. The forecaster uses the T0 wave analysis plus the T + 12 isobaric prog to produce a T + 12 wave prog. Then the T + 12 wave prog plus the T + 24 isobaric prog yield the T + 24 wave prog. Finally, the T + 24 wave prog plus the T + 36 isobaric prog yield the T + 36 wave prog. Numerical wave models use a similar procedure but with a much shorter time step.

It should be noted that the analyses give Combined Wave Height, while the progs give Significant Wave Height. These parameters have very different definitions. But it has often been noted that what human observers report for wave height is very close to what a waverider would report as Significant wave height. Thus, for operational purposes, we make no attempt to distinguish one from the other.

OPERATIONAL PROBLEMS

Any forecast program depends ultimately on the quantity and quality of the data which go into its analyses. At METOC, our program is no different. Our wave data come from buoys and from ships of opportunity. We have problems with both quantity and quality. Much of the effort which goes into analyzing sea state is used to combat these problems.

The window we use for both our surface isobaric analysis and our wave analysis covers much of the North Atlantic. It is a vast area which includes the world's busiest shipping lanes. Yet we frequently get as few as one or two dozen plotted wave reports.

In preparing an analysis, an analyst must look critically at every report. There are many reasons why an analyst could suspect a report :

- observing wave height is difficult (even for a trained observer), yet many shipboard observers are untrained;
- adjacent ship reports may conflict with one another;

- individual ship reports may not fit with history or the expected pattern;
- ships sometimes report swell almost identical to wind waves and coming from almost the same direction; or
- sometimes the direction from which a swell is reported to come is unrealistic or unexpected.

Unfortunately, ships do not report regularly. Only a few of the ships on any one map will be found on the previous map. It is even rarer to find the same ship plotted on three successive maps. Thus if a ship's report is suspicious, an analyst can only rarely look at that ship's previous report.

Deadlines present an important constraint. At present, the first wave product, the wave analysis, must be transmitted at T0 + 4. The final wave product, the 36 hour prog, must be transmitted at T0 + 6. This schedule cannot be changed much without seriously inconveniencing users.

OPERATIONAL SOLUTION

At present, the only way an analyst can get around the problems of quality and quantity of data is to consider the current wind field and the historical wind- and wave-fields. Operationally, the analyst gets additional input from a T-6 Wave Analysis, and a T0 Surface Isobaric analysis. This solution has been in use since METOC began sea-state forecasting.

REMOTE SENSING - A NEW SOLUTION

You will note that the previous two sections were titled Operational Problems (a plural) and Operational Solution (a singular). This was not accidental. There are many problems with quality and quantity, but to now there has been only one solution which works in a time- limited, operational setting. Remote sensing offers the first real hope for a new solution.

But although we have reliable satellites with reliable sensors, we still have to work out how to get the resulting data to the forecaster's desk in a usable format, and in time to be useful. Specifically, we must find ways to:

- incorporate asynoptic data into synoptic analyses;
- deliver the data to forecasters in time to affect their decisions; and
- deliver the data in a usable format to the forecaster's workstation.

WAVE MODELLING - A NEW SOLUTION

The newest wave models produce useful guidance. The ones which run on mainframe systems give results in time to affect a forecaster's decisions. These models have reached the stage where the quality of the output depends most on the quality of the input wind field. Thus we need interactive models. A forecaster should be able to send an edited wind field to the model, then display and, if necessary, edit the resulting wave field before issuing the final product. This means that the model should be designed to be run from a forecaster's workstation, and that the workstation needs the power to produce its output in time to meet deadlines.

SUMMARY

To sum up, satellites can deliver large quantities of data. If satellite data can be assimilated into operational routines, it will improve the quality of wave analyses. New models can deliver useful, timely guidance, which can improve the quality of forecasts. Model nerformance could itself be improved just by supplying better wind fields. Thus we need a way to get satellite data to the forecaster and into the analysis program, and a way to allow a forecaster to improve the wind field before a model runs. Furthermore, all of this must be done under the constraints of tight deadlines.

The resources with which to tackle these problems are not available in the operational world. We look to researchers for the solutions. But we would like to be involved. It is essential that operational fore- casters have input to the solutions to operational problems.

WAVE MODELLING FROM PERSPECTIVE OF OPERATOR

Vincent J. Cardone
Oceanweather Inc.
Cos Cob, CT

ABSTRACT

A wide array of wave models are available to operators, including parametric significant wave modes, and spectral wave models utilizing first-(1G), second-(2G) and third-generation (3G) physics. One can find variants of each of these model classes operational at real-time forecast centres (the third generation WAM model is now operational to ECMWF). For assessment of extreme and normal wave climates, mainly 1G and 2G spectral models have been applied in a hindcast mode. The Sea Wave Modelling Project (SWAMP, 1985) has provided extremely useful insight to model operators in its revelation of the large variability in model behaviour as a function of the complexity of the wave regime.

Despite SWAMP, and the more recent intercomparison of models in the LEWEX, an objective assessment of alternative model skill as a function of the wave regime and the desired wave property (integrated wave parameters versus directional wave spectra) remains elusive to the impartial operator. For example, despite its greater sophistication, computational burden and potential, WAM has not exhibited conspicuously greater skill in hindcasts than highly developed and tuned 1G (e.g. ODGP) and 2G (e.g. ADWAVE, HYPA, VAG, WINCH) models. We attribute this mainly to the generally large errors which characterize marine wind fields used to drive wave models. However, a recent field program (SWADE) has, probably for the first time, enabled the specification of wind fields of sufficient accuracy to reveal the incremental benefit of 3G models. 3G models will continue to gain acceptance and can be used for operational forecasting and hindcasting if computer resources allow. However, for most applications, validated 1G and 2G models may continue to be used, but model performance should be checked against measured data whenever possible, and especially when modelling esoteric meteorological regimes.

WHY DO WE OPERATE WAVE MODELS?

Extreme Wave Climate Assessment for Structure Design

Operational Wave Climate Assessment for Operability

Real Time Forecasting

Applied Research

SPECTRAL WAVE MODELLING

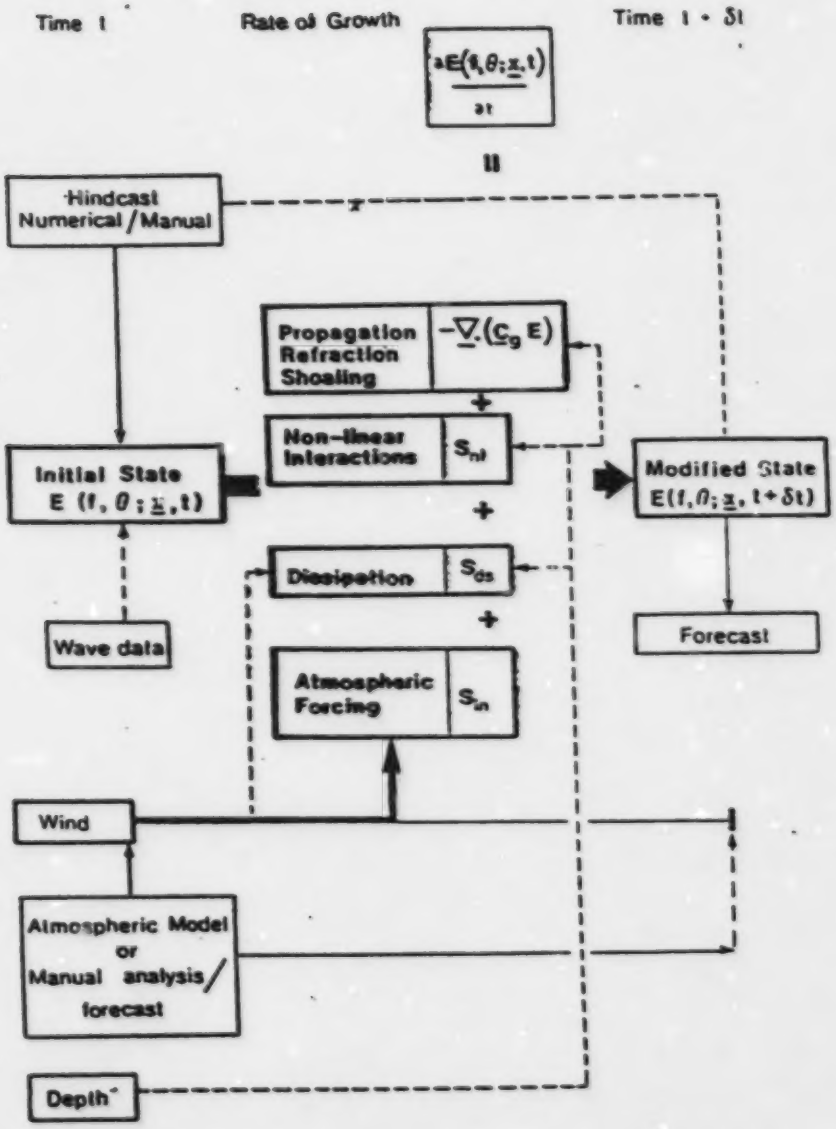
Selected Milestones

1957	First operational model based on transport equations (France, Gelci et al.)
1957	Miles-Phillips theories
1964	Pierson-Moskowitz fully developed spectrum
1966	Proposed global wave model Pierson-Tick-Baer (1966)
1968	First models incorporating non-linear source term (Barnett---)
1973	JONSWAP fetch-limited wave growth experiments
1974	Highly tuned 1-G models (e.g., ODGP) emerge SOWM operational in NH at FNOC
1979	SWAMP group formed and tests carried out - Exact NL tested
1984	WAM group formed (SWAMP results published) - 3G-WAM tested
1986	SOWM replaced by GSOWM, NMC acquires global model
1987	ECMWF implements 3G-WAM global model

WAM Model Development Group formalized (MDG)
Hasselmann, Janssen, Komen, de Voogt, Cardone, Cavalieri, Gunther, Guddal, Zambresky

ICSU/SCOR WG 83 (Waves) created:
Cardone, Cavalieri, Donelan, Francis, Graber, Rosenthal, Hasselmann, Holthuijsen, Komen, de Voogt, Guddal

INTRODUCTION TO WAVE MODELLING



Extreme Wave Climate Assessment for Structure Design

Tropical cyclones (first GMEX, 1972 with ODGP)
Extratropical cyclones (first G. Alaska, 1978)
Tropical monsoonal flows (Borneo, SCS, 1982)
Southern hemisphere (New Zealand, Australia, Africa)

Requirements

peak significant wave height and associated wave period and direction in a storm at a site

Conclusions

in most NH basins and some SH basins, calibrated 1G and 2G models yield scatter index of 10-15% and bias of less than 0.5 m in HS, provided "best" wind fields are developed; 3G models at least as skilful but regimes tested more limited so far.

Operational Wave Climate Assessment for Operability

North Atlantic climate based upon METOC series
U.S. 20-year hindcast studies (1956-1975)
3-year East Coast wave analysis series
30 year Norwegian hindcast
Regional studies now feasible on workstations

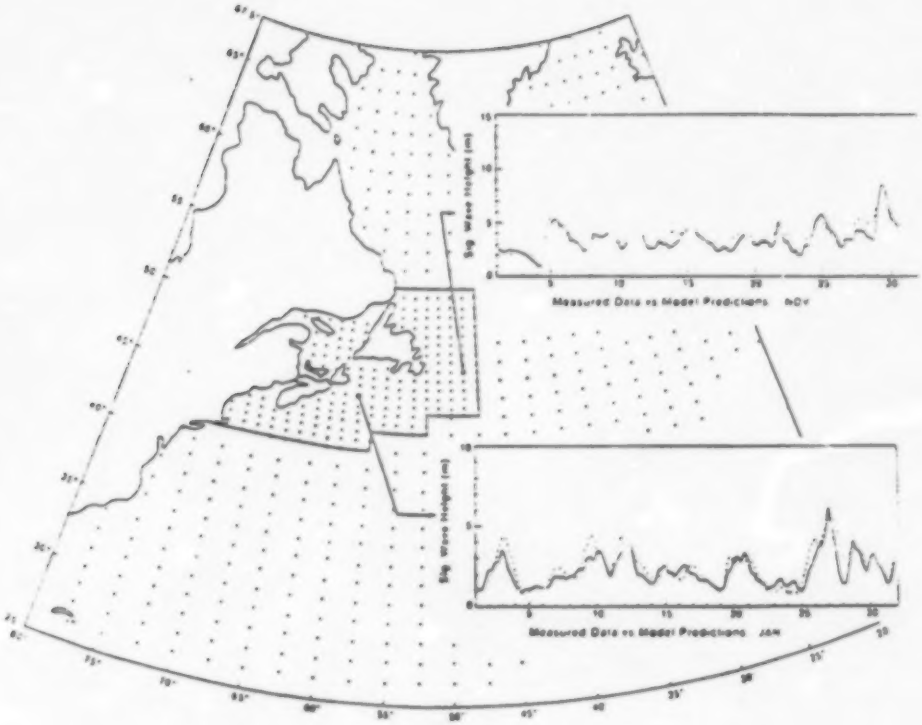
Requirements

HS, TP time series
Characteristic spectra

Conclusions

1G and 2G spectral show advantages over parametric approaches, 3G models not yet used

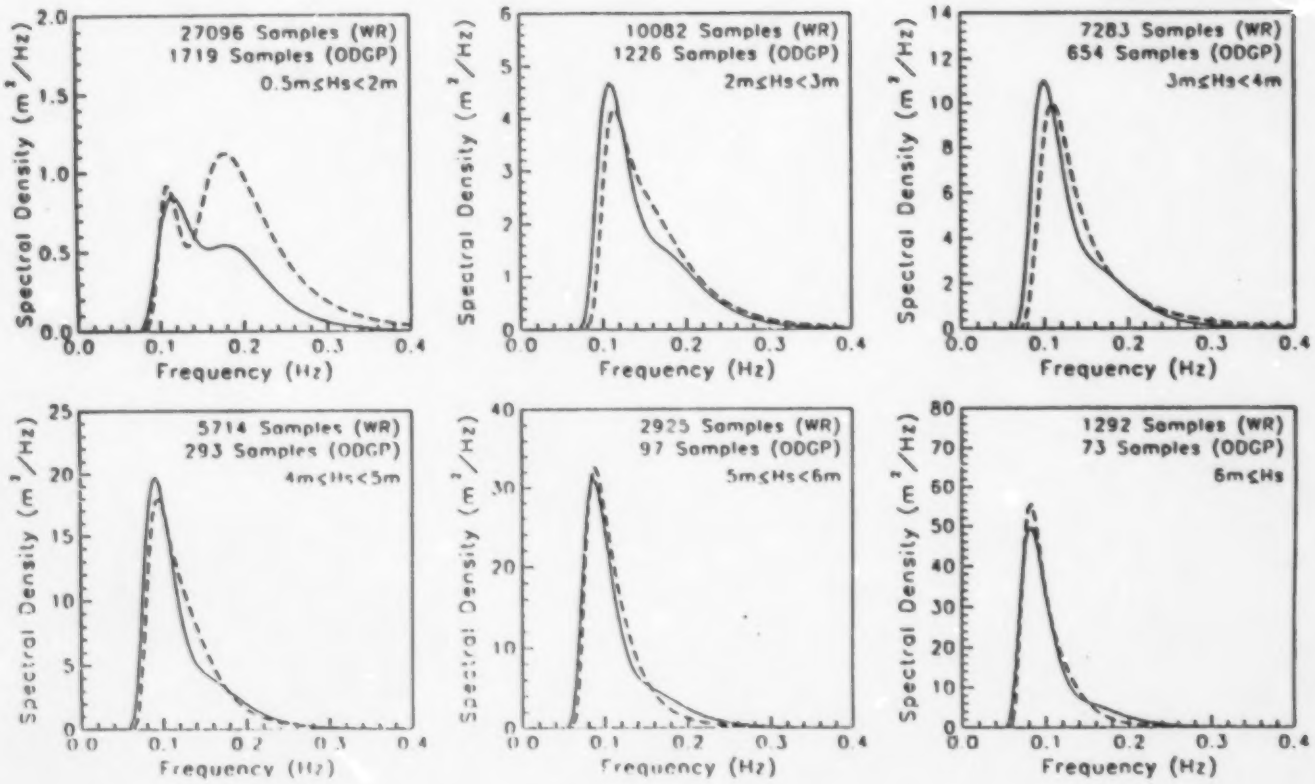
wind field errors larger than in dedicated hindcast studies, therefore scatter index is typically 20-30% in HS



Operational ODGP wave hindcast model grid. Coarse grid points shown at spacing of 1.25° latitude by 2.50° longitude. Domain of fine mesh nested grids Canadian Scotian Shelf and Grand Banks shown.

MOST PROBABLE SPECTRA

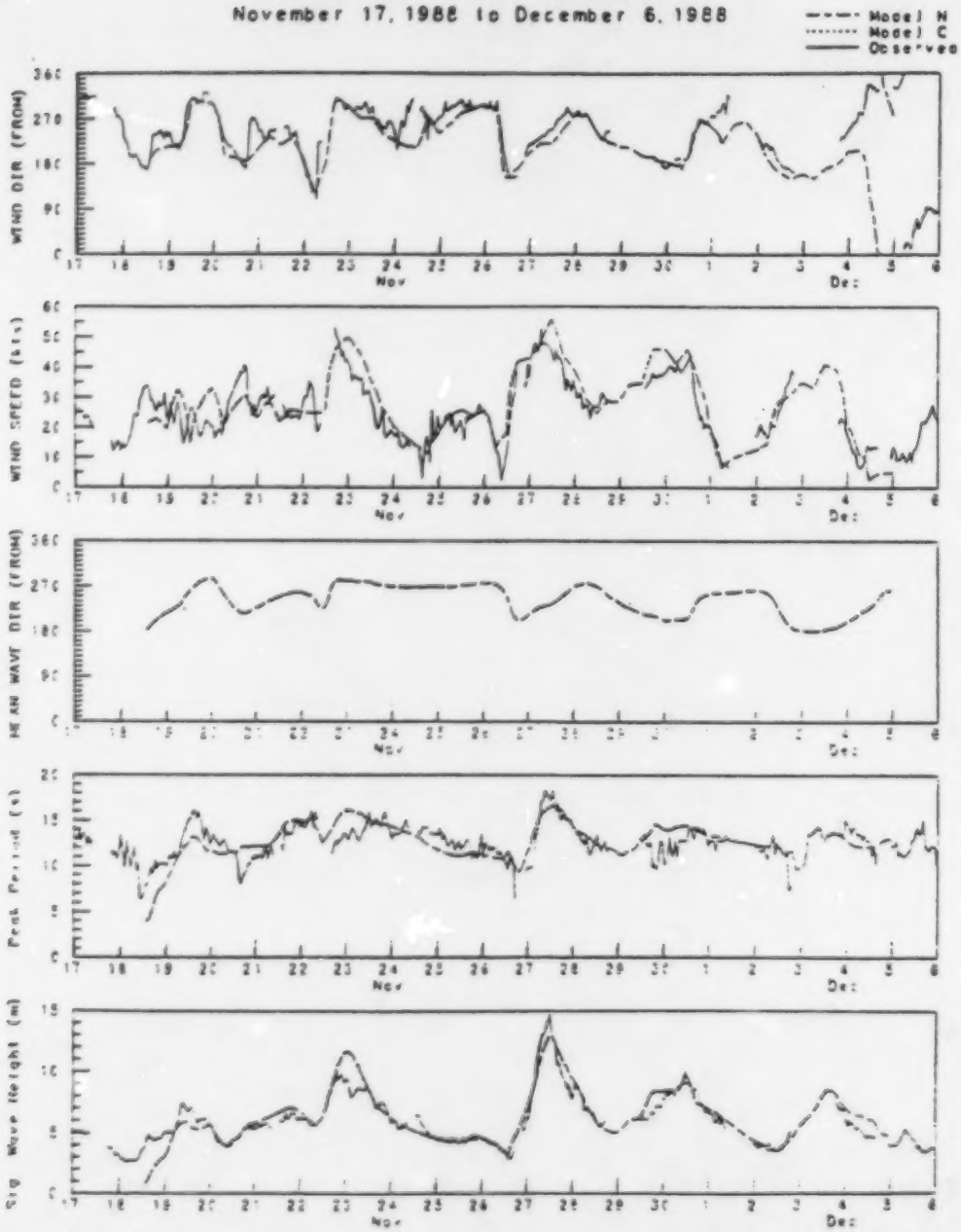
EAST COAST AREA 6 - SABLE



WEST COAST STORM VERIFICATION

GRID POINT 768 - WR 46004

November 17, 1988 to December 6, 1988



Real Time Forecasting

Spectral models introduced in 1970's, now widespread (e.g. GSOWM, WINCH, VAG, ODGP, WAM)

Requirements

depends on forecast use; at least HS, TP time histories, but ship response requires full 2D spectra

Conclusions

wind errors dominate beyond forecast horizon of 24 hours, useful skill to about 96-120 hours

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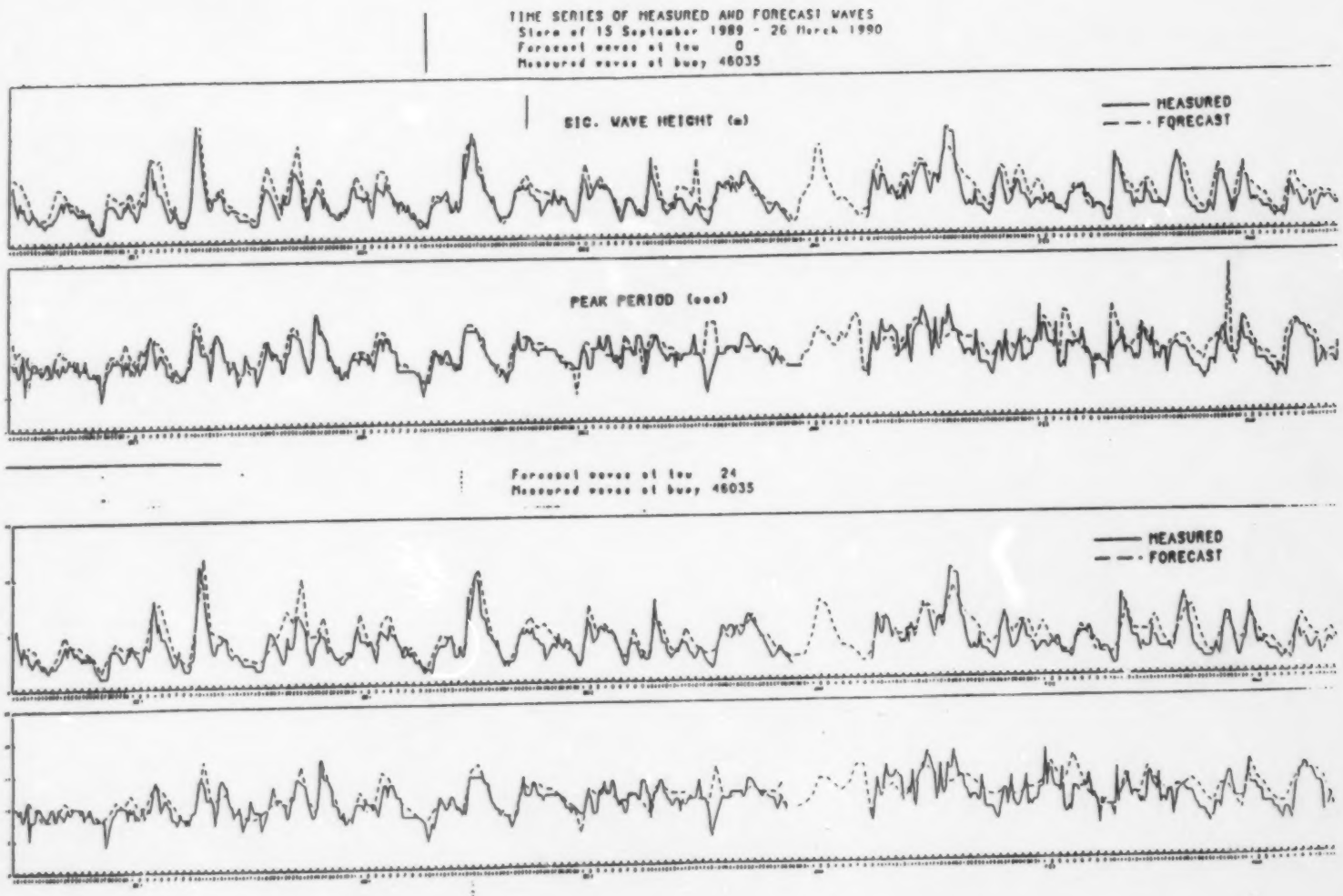

TIME SERIES OF MEASURED AND FORECAST WAVES
Start of 15 September 1989 - 26 March 1990
Forecast waves at tau 0
Measured waves at buoy 46035
SIG. WAVE HEIGHT (m)
MEASURED
FORECAST
PEAK PERIOD (sec)
Forecast waves at tau 24
Measured waves at buoy 46035
MEASURED
FORECAST

Applied Research

Serve as ground truth for remote sensors/vice versa

Couple to other models (e.g. oil slick models)

Wave dependent drag

SAR image retrieval and inverse modelling

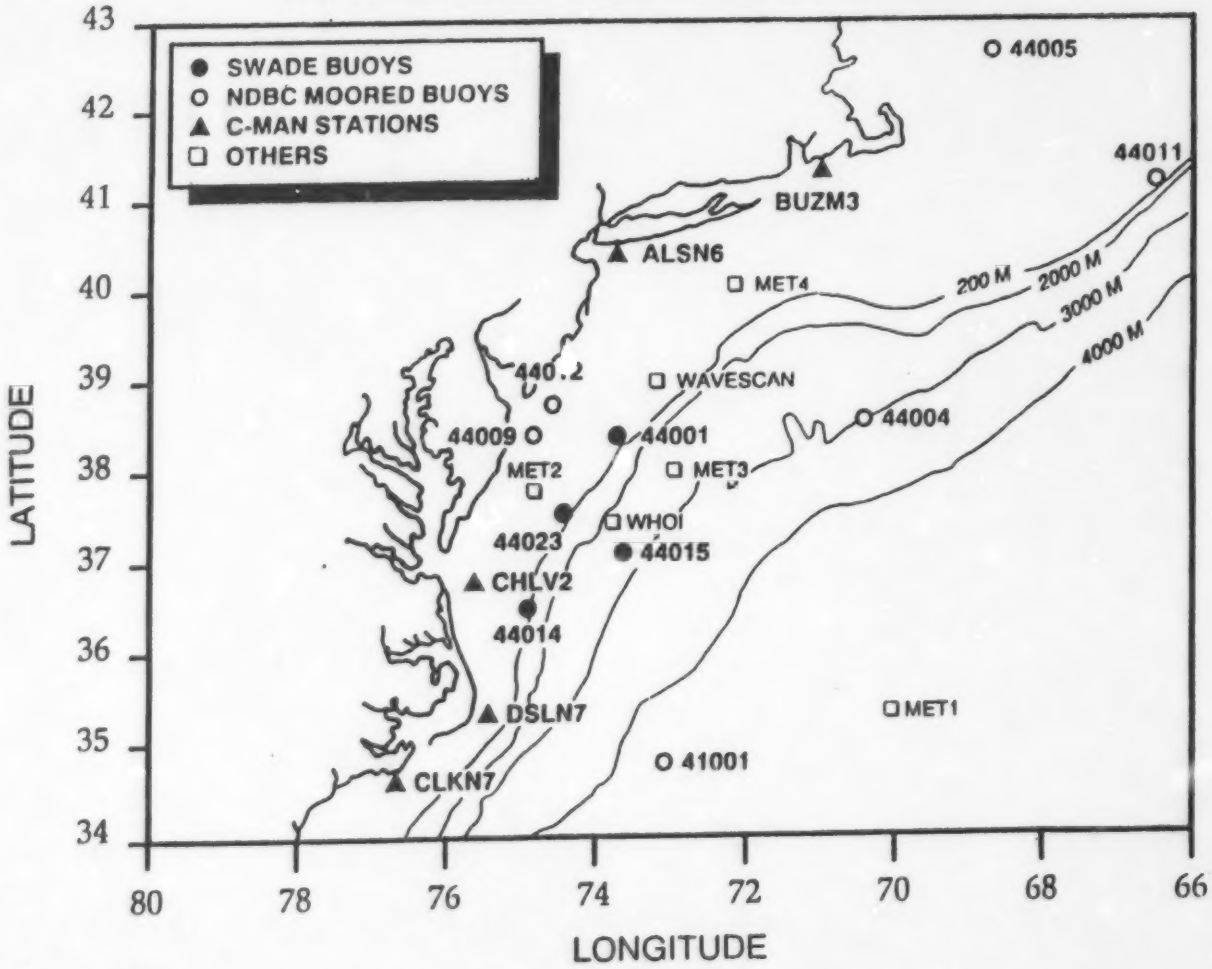
SWADE IOP INTENSIVE WIND FIELD REANALYSIS

PRINCIPAL OBJECTIVES

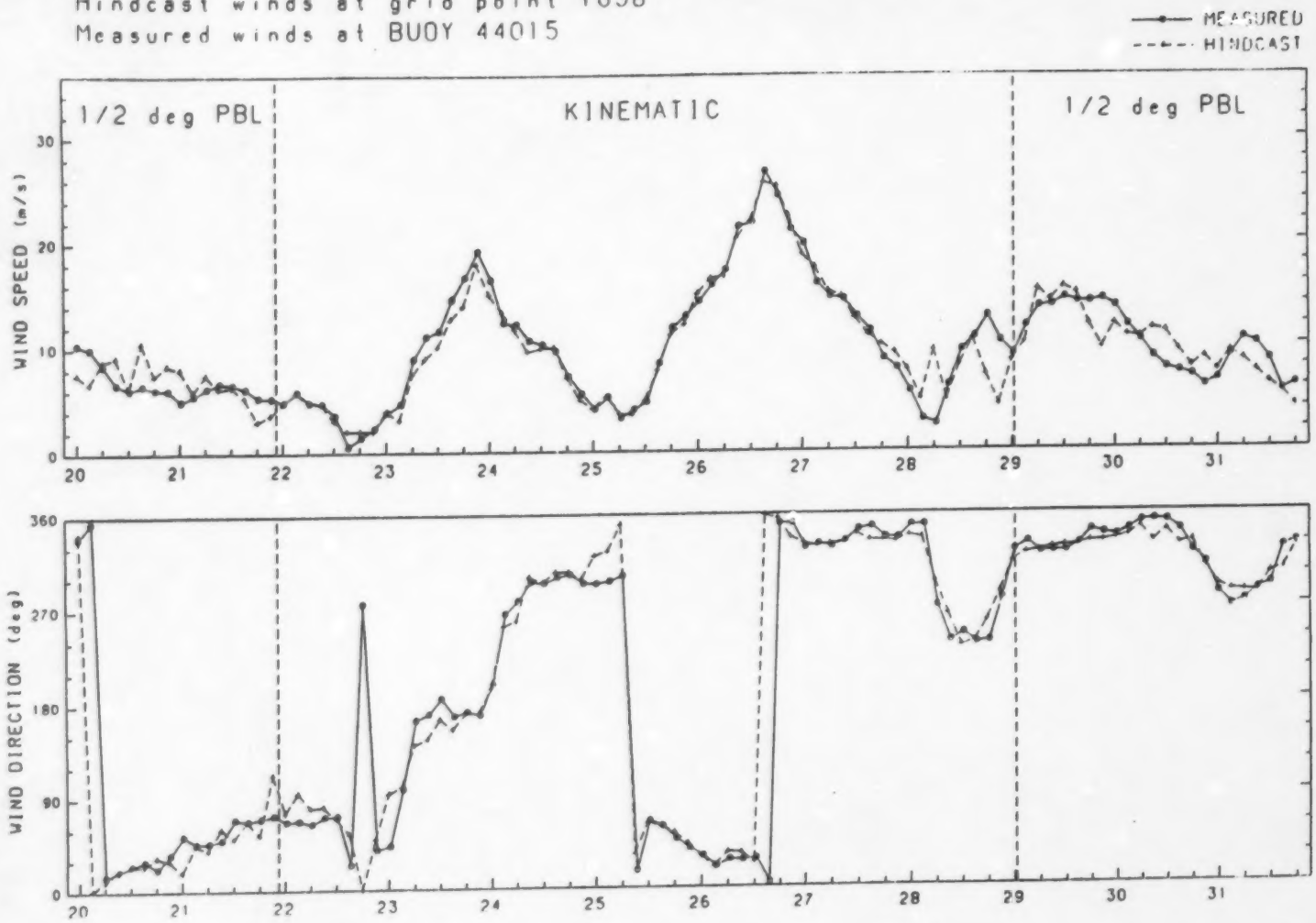
1. reduce wind errors to levels where comparative analysis of model runs and SWADE wave measurements reveal deficiencies in physics, not winds

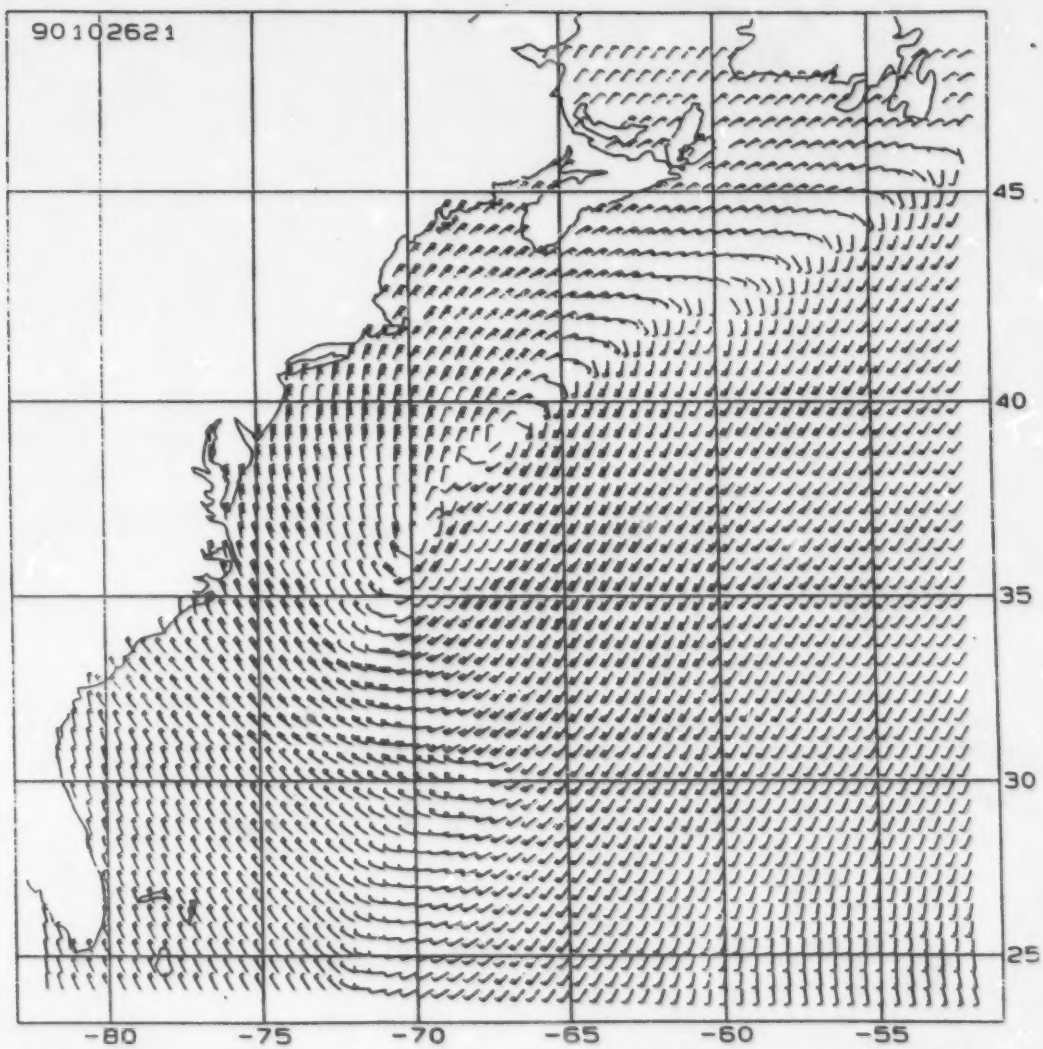
2. develop bench-mark wind field for testing of models in realistic complicated wind forcing (a la SWAMP)

SWADE BUOY LOCATIONS



TIME SERIES OF MEASURED AND HINDCAST WINDS (kinema)
Storm of 20 October - 31 October, 1990
Hindcast winds at grid point 1658
Measured winds at BUOY 44015

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CONCLUSIONS AND CONCERNS

Wave modelling is one of the great success stories in numerical environmental simulation.

Especially since SWAMP, a few very skilful 2G models have emerged, at least matching the skill of the best 1G models of the PTB/ODGP heritage.

WAM is potentially far more powerful than 1G or 2G model but demonstration of this has been severely hampered by wind field deficiencies. SWADE and possibly some ERS 1 programs will soon change this.

The impartial operator needs better objective measures to evaluate model accuracy and "benchtest" performance:

> Fetch/duration test a la SWAMP, but include check for similarity of wave growth (several wind speeds)
>
> Turning wind - sudden 90 degrees and slew 30 degrees/6 hours
>
> Stationary and moving tight cyclone
>
> Complicated extratropical cyclone regime
>
> Swell propagation from distant storm
>
> All of the above in shallow water and pack ice!

Wave models do not provide highest single wave information - "rogue wave" important for many practical problems

Because physics is still uncertain, even 3G models may not be reliable for rare and peculiar meteorological forcing:

> fully developed seas in wind speeds above 40 knots
>
> fast moving tropical cyclones
>
> orthogonal fetch generation zones

The three most outstanding impediments to skilful wave modelling are:

> wind field errors
> wind field errors
> wind field errors!

DEVELOPMENTS IN WAVE MODELLING

F.W. Dobson
Bedford Institute of Oceanography
Dartmouth, NS

The wave modelling and data assimilation R&D effort at BIO has established a widespread network of collaborators, including most of the world's experts, in government agencies, universities and the private sector. This network is open to PERD through the funding of our R&D. Through it, we perform joint theoretical and experimental projects which utilize resources far beyond those the PERD funding can provide. The wave modelling effort is presently concentrated on a) understanding the marine wind and wave fields and their coupling, b) improving numerical models of the behaviour of the fields, and c) providing, through contracts and our own developments, working operational models for the user community. Work is concentrated in the specific topic areas of basic wave physics, wave-ice interactions, wave-current interactions, and data assimilation including adaptive wind-wave coupling modelling.

We have participated in a number of large field programs, including CASP-I, LEWEX 87,89, LIMEX 89, SWADE, ERS-1 CAL/VAL, and CASP-II. From PERD-sponsored work we have made important contributions to basic wave physics, wave-ice interactions, wave-current interactions and in several areas of data assimilation.

Notwithstanding the strides make in forecasting over the past decade, the major problem facing the wave modeller today remains that of estimating the marine surface wind field, particularly in rapidly-developing weather systems. Over the last five years it has become clear that the wind stress which causes the waves to develop is strongly related to the sea state. No operational model allows for this feedback and we have shown that it matters. The calibration and assimilation into the models of satellite radar wave and wind information will go a long way to alleviate the problem. The work is in progress, both at BIO and elsewhere.

INTRODUCTION

The Wave Group at BIO consists of three individuals: Fred Dobson an experimental physicist specializing in air-sea interaction problems, William Perrie, a theoretical physicist with interests in nonlinear problems, and Bechara Toulany, a physical oceanographer and numerical modeller. The Group has been existence since 1981, when the latter two began at BIO with support from PERD.

PROJECTS

The Group is involved in advanced wave modelling, wave-current and wave-ice interactions, data assimilation, wind-wave coupling studies, and radar remote sensing.

ADVANCED WAVE MODELLING

Work in advanced wave modelling has been concentrated in two main areas. The Group is an active participant in the WAM Group, and has contributed directly to the development of the WAM model (Perrie, Toulany). In addition several important papers have been published with D. Resio of Offshore & Coastal Technologies on efficient and accurate computations of wave-wave interactions (Perrie).

WAVE-CURRENT INTERACTIONS

Funded work on wave-current interactions began in 1990 with a state-of-the-art literature survey by Resio. This has been followed with the development of a research model containing wave-current interaction terms based on joint work with A. Jenkins of the IBM Bergen Research Centre (Perrie).

WAVE-ICE INTERACTIONS

A research project on the scattering of waves by floating ice has been carried out (Perrie, Rahman at TUNS). A research model with wave-ice interaction terms based on the work of Masson is presently under development (Perrie & student). During the analysis phase of the LEWEX Project the BIO Group produced the only wave fields which included in the hindcast the presence of the ice edge; the results were significantly different from the other model outputs, indicating the importance of including the presence of ice fields in high-latitude wave forecasts.

DATA ASSIMILATION INTO WAVE MODELS

Work on assimilation of data into wave models has been initiated in a variety of areas. The optimal interpolation of measurements of sea level pressure over the ocean has been the subject of a published article (Perrie, Toulany). It has been the precursor to work in progress on assimilating GEOSAT radar altimeter wave height and wind speed data into a model (Perrie, Toulany). An RDDP/PERD-sponsored contract is presently under way (Dobson, Vachon at CCRS, Khandekar at AES, Dunlap at MacLaren-Plansearch SNC/Lavalin) to incorporate an algorithm, developed by S&K Hasselmann at the Max-Plank Institute for Meteorology, into the ODGP wave model. This will make the model capable of assimilating the wave spectra from satellite Synthetic Aperture Radar.

Work is also under way in producing a research wave model which will allow a feedback between the sea state and the wind stress (Perrie, Wang). It has involved the design of a special-purpose atmospheric boundary layer model and the ability to iterate the wind and wave fields at each grid point to achieve an accurate estimate of the coupling between them.

WIND-WAVE COUPLING

The CASP-I experiment in the winter of 1985/86 produced an excellent data set on fetch-limited wave growth from an array of buoys moored off Martinique Beach, NS. The data were analyzed in conjunction with boundary-layer flights by an NRC aircraft (P.C. Smith and I. MacPherson) which defined the offshore development of the wind and wind stress fields. The resulting publication on fetch-limited wave growth laws has changed our understanding of the process and the calibration of the growth parameterizations used in forecast and hindcast models (Dobson/Perrie/Toulany).

The implications of work coming out of recent air-sea interaction experiments (HEXOS) that the wind stress may double in the initial stages of wave growth, has been investigated and published (Perrie, Toulany).

In November 1991 a field experiment was carried out on CSS "Hudson" on the Grand Banks. Shipboard wind stress measurements made during this experiment will be used in conjunction with modelled and measured wave fields to provide an accurate determination of the relation between the wind stress and the state of development of the wave field (Dobson/S.D. Smith/R.J. Anderson).

RADAR CALIBRATIONS & VALIDATIONS

The November 1991 experiment on the Grand Banks also performed an in situ calibration and validation of the Synthetic Aperture Radar on the ESA "ERS-1" satellite. Aircraft from CCRS and NASA underflew the satellite, and the in situ calibration was coordinated with forecasts from the AES operational wave model: all in situ measurements were situated on model grid points. Data were collected from shipboard and buoy-mounted meteorological and wave sensors, marine radar, land-based HF radar, and airborne SAR and Radar Ocean Wave Spectrometer. The ERS-1 scatterometer data will also be investigated in the light of the in situ measurements, as well as radar altimeter data from aircraft and spacecraft.

Work has begun with the ERS-1 Cal/Val experiment on a program of validation of the data from satellite radars. Collaborations with CCRS, AES, NASA, ESA and JSA have been put in place. The deliverable will be improved algorithms relating the physical quantities measured by the radars to the state of the sea surface. These algorithms can then be used by modellers to assimilate the satellite, shipborne and land-based radar information into prediction models for ocean winds and waves. Because the algorithms from all the radars are sensitive to sea surface parameters of importance to the models' predictive abilities, such as wind stress, the assimilation procedures will enable the modellers to estimate such quantities with unprecedented accuracy, on a global scale, and based on measurements of uniform accuracy (Dobson, Vachon at CCRS).

Studies of marine radars are in progress, in collaboration with F. Ziemer and W. Rosenthal of GKSS Hamburg (the originators of the technique). These have already led to the transfer of the technology to MacLaren-Plansearch/SNC-Lavalin, which has delivered a system to the LASMO production rig on the Scotian Shelf. The system was pilot-tested successfully during the ERS-1 Cal/Val cruise, and the images from it, along with another set from Royal Roads (RRMC), will be part of the satellite SAR calibration. Since the marine radar provides the wave travel direction, it resolves the 180° ambiguity inherent in SAR spectra (Dobson, Buckley). Similarly, wave heights and currents collected by the NRSL HF radar on Cape Race can be used to enhance and extend the information available from the SAR (Helbig).

FIELD EXPERIMENTS

We have participated in a number of field programs, including CASP-I, LEWEX 87,89, LIMEX 89, SWADE, ERS-1 CAL/VAL, and CASP-II. With the data sets from the experiments we have made or will be making important contributions to basic wave physics (new wave growth relations from CASP-I, and efficient and accurate technique for computing wave-wave interactions, new growth laws in turning winds), wave-ice interactions, wave-current interactions and in several areas data assimilation.

GOALS

The basic goals of the BIO Wave Group's research and development are:

- understanding the marine wind and wave fields and their coupling;
- improving models of the behaviour of the fields; and
- providing, through contracts and our own developments, working operational models for the user community.

NETWORK

Through its extensive network of scientific colleagues worldwide, the Group brings to PERD a wide range of consulting expertise (e.g. the transfer of the marine radar technology from Ziemar & Rosenthal and the transfer of the SAR data assimilation technique from S&K Hasselmann, both to MacLaren-Plansearch/SNC-Lavalin). A partial listing gives an idea of the extent of the network: all the agencies listed have a close interest in the BIO efforts.

Government labs:

DFO (PCS, MEDS, NAFC, CCIW, IOS)
AES (MSRB, CCC)
DND (METOC, DREA)
EMR (CCRS, RDDP)
ESA (ERS-1)
JSA (JERS-1)
NASA/GODDARD
MPI WAM/ECMWF
CSIRO
IAP Moscow
WHOI
NCAR
KNMI
NPL Teddington
Rennel Centre Southampton
Riso Physics
Qingdao Marine Forecast Centre
NOAA Miami
CNEXO/Ifremer

Industrial consultants:

OCTI (Resio); OceanWeather (Cardone); GKSS (Rosenthal, Ziemer);
IBM Bergen Science Centre (Jenkins);
MacLaren-Plansearch/SNC Lavalin (Eid, Dunlap);
OceanRoutes/Seimac; MetOcean; AXYS; Arctic Sciences; Seaconsult;
Northern Radar Systems Ltd.

Universities:

Dalhousie, TUNS, UBC, UVic, RRMC, John Hopkins/APL;
McMaster/CRL; MUN/C-CORE, Nova, CUNY, U Washington, IFM Kiel, Tohoku,
Tokai, Beijing

PRESENT STATUS OF WAVE MODELLING

1. The satellite age has begun in earnest on July 16, 1991 with the launch of ERS-1. Field experiments to calibrate and validate the satellite radar systems are ongoing. The ERS-1 and JERS-1 satellite data will provide fertile ground for research for the next decade; Canada's RadarSat will be launched in 1995.

2. To cope with the expected flow of satellite data from the entire marine area of the globe, forecast modellers are scrambling to implement data assimilation methods for it. In some cases, as with the Scatterometer, this will involve fundamental changes to the way the models treat the physics. The short-term goal is simply to get the stream of satellite data assimilated into the models, to enhance their coverage over the sea. The longer-term goal is to use the interrelationships among the various radars in the assimilation process to obtain estimates of a variety of hard-to-obtain sea surface parameters, such as wind stress.

3. The advent of 1. and 2., combined with new experimental results, has demanded that we couple our wind-wave models to allow for the sea state-wind stress feedback. It is now understood that the wind stress for a given wind speed can be double its normal value in the presence of rapidly-developing waves. The field measurement program and the modelling work is ongoing here and elsewhere (in particular at ECMWF); our contribution is a modelling system of moderate size and complexity containing the essential physics (a new atmospheric boundary-layer model, the latest measured relation between wind stress and sea state).

4. Notwithstanding the urgency of learning how to model the effects of ice and surface currents on waves, the central problem remains: for the purposes of operational wave forecasting we cannot specify the marine wind field accurately or completely enough (e.g. LEWEX experience). We are far from having operationally-useful prediction models.

5. Canada is committed to launching a SAR satellite in 1995. The resulting sharp focus on SAR by our space agencies has committed some PERD-related resources to SAR studies. It is difficult in the face of this sharp focus by a major funder to maintain a balanced approach to the problems of assimilating all types of radar data in wave models.

6. In spite of extensive R&D efforts both at BIO and elsewhere we remain embarrassingly short of reliable seagoing instruments to carry out the satellite sensor calibrations and validations we are planning. The reason is not that such instruments don't exist, but that they don't work reliably at high sea states in high-latitude, heavily-fished coastal environments where ice and icing conditions are prevalent throughout the winter months. Four areas come immediately to mind: marine radars for sensing waves and ice, meteorological buoys, directional wave buoys and bottom-mounted ADCP systems designed to remain in place for more than a few days.

FUTURE DIRECTIONS

1. There are strong indications, for example the recent "Halloween storm" on the Canadian east coast, that existing representations of the strongly nonlinear wind-wave coupling process by simple extremal statistics is inadequate for the design engineer or for the impact studies used by planners. A more physics-based representation is sorely needed which accounts for the various modes of nonlinearity known to exist in the system.

2. The next step increases in skill in marine weather (and hence wave) forecasting will come from a) assimilating the newly-available global, all-weather satellite radar wind and wave fields into b) models which allow for the sea state-wind stress feedback. In Canada this will be achieved first on limited-capability forecast models like the AES 'C-SOWM'.

3. The emphasis will be on assimilation of SAR data: we have a head start there. Scatterometer and Altimeter data will be assimilated operationally only when the algorithms are worked out which relate the radar wave and wind estimates to the physics of the marine meteorological and ocean surface wave forecast models. The full payoff in enhanced forecast skill

will not be realized until all the radar data and the sea state-wind stress feedback can be part of the assimilation, so full utilization can be made of the cross-links among them.

4. Alongside the effort in the area of nonlinear interactions, we are making headway in wave-current and wave-ice interactions. They are very tough problems theoretically, and little reliable experimental data exist (e.g. CASP-I & LIMEX 89). Continuing support for this modelling work is essential. Providing they are calibrated so that ice properties as well as coverage are provided, the new satellites will help, particularly ERS1, JERS1 and, if it is launched soon, RadarSat. So we need to ensure the calibrations get done as the opportunities arise, with carefully-designed field studies. Close collaborations with the space agencies will be essential, as will the opportunity to put specialized equipment on drill rigs and production platforms in the Canadian offshore.

5. Progress in data assimilation, coupling of wind and wave models, and validation of satellite radar data are all going to require a closer working relationship with AES Downsview and RPN Dorval. These relationships have been difficult to maintain so far. We anticipate an increase in the number of joint projects and modelling efforts.

6. Workstation-based third-generation wave prediction models with the Resio/Perrie efficient S_{NL} calculation will be available soon.

7. Perceived inadequacies in extremal statistics as planning tools and the possibility of climate changes brought about by global greenhouse warming will call for revisions of wave climate statistics for all areas.

SUMMARY - EXISTING AND DEVELOPING RESEARCH AND OPERATIONAL WAVE MODELS

V. Swail
Atmospheric Environment Service
Downsview, ON

"Wave modelling can be regarded as one of the great success stories in numerical environmental simulation" - that was one of the primary conclusions of the wave modelling session. Unlike modelling efforts in other subject areas, there has been a concerted, coordinated modelling effort in wave research for nearly 20 years. As a result, the number and type of wave models in current use are few, and those which are in use have well-proven ability to accurately describe the sea state in most conditions. The modelling effort has culminated in the development by the international wave modelling group (WAM) of a 3rd generation (3-G) wave model based on physical principles rather than empirical considerations. Recent tests have shown that, given high-quality wind fields, the 3-G model can produce near perfect representations of sea state, for many sets of environmental conditions.

The success enjoyed in wave modelling does not mean that there is still not work to do in this area, however. Because the physics is still uncertain, even 3-G models may not be reliable for rare and peculiar meteorological forcing. There still remain many questions regarding the modelling of shallow water waves, waves in unconsolidated pack ice, wave-current interactions, and assimilation of wind and wave measurements. Continued research into these areas is essential, and participation in international modelling efforts such as WAM represents an excellent way to accelerate and enhance this research.

A recurring theme throughout the wave modelling sessions, and in fact throughout the other modelling sessions as well, was the need for better marine wind fields as input to the models. The lack of high-quality marine surface wind information was considered to be the most important constraint to the accurate representation of sea state. Even with perfect wave models, the wind field errors associated with conventional observational and modelling efforts, especially spatially-coherent errors, will produce unreliable sea state estimates. Therefore, it must be ensured that any further research effort, not only for waves but for other ocean response models as well, contains a significant effort devoted to the improvement of marine wind observations and modelling (including the modelling of surface wind stress as well as wind speed). The continued development of marine wind models, and remote sensing of marine winds, especially by satellite, are two areas of primary importance.

CSOWM
- CMC winds directly
- no shallow water
- out of grid swell unaccounted for
- includes shallow water physics, 3-G terms but not operationally
- requires super computer, especially for shallow, 3-G
- suitable for nowcasting, forecasting

DONELAN
- parametric spectral
- no shallow water
- no swell
- suitable for enclosed water bodies for nowcasting, forecasting
- runs on PC

PACWAV/ NATWAV
- allows man-machine mix; interactive graphics
- no shallow water
- out of grid swell unaccounted for
- runs on a workstation
- suitable for forecasting and engineering

SPECREF
- CMC surface winds
- site specific
- includes shallow water
- runs on a PC

WAVAD
- 2-G spectral model
- includes shallow water
- no diffraction, reflection
- no wave-current interactions (as those above do not)
- runs on a PC 386
- suitable for nowcasting, forecasting

WAM
- full 3-G model
- has shallow water physics but not bottom topography everywhere
- latest version (cycle 4) has wave-current interaction
- research only at this time (in Canada)

Note: Operational is defined as both for forecasting and hindcasting purposes.

NEEDS FOR OPERATIONAL (HINDCAST AND FORECAST) AND RESEARCH WAVE MODELS

INDUSTRY

Feasibility Studies

- maybe run of previous model now in data base, or use of a simple model such as SMB, for example

Drilling Criteria

Design Criteria

- survivability
- area, local, site
- frequently updated for maximum confidence, especially if climate changing

Operational Limits

- suitability for safety, economics of routine operations

Operational Support

- real time forecasting
- reliable models to give advance warning (especially to 24 hours) without excessive

false alarms
- emergency response

Assessment of climate change impacts on design criteria

REGULATORS

Environmental assessment and regulatory approval process

Design Criteria

- as for industry

Operational Limits

- as for industry

Operational Support

- as for industry

Assessment of climate change impacts on design criteria

OPERATORS

In-situ verification

Data, including satellite data, in a usable form in real-time

Range of wave models of varying complexity

Guidance on what level of model to select for specific applications

Interactive capability with models for modification of input and output fields for analyses in progress (for regional rather that centralized, e.g. CMC, activities)

Need from researchers

- fetch/duration test a la SWAMP, including check for similarity of wave growth
- turning wind cases
- stationary and moving tight cyclones
- complicated extratropical cyclone regime
- swell propagation from distant storms
- how to assimilate wind, wave, coupling information into models
- all of these in shallow water and pack ice

Highest single wave information

High quality wind analyses and model output

RESEARCH COMMUNITY (WAVES AND OTHERS)

In-situ verification

Wind and wave information for operational planning of field activities

Wind and wave data from models

LINKAGES

Existing	Type
National Waves Committee	Res - Dev - Op - User
PERD Task 6 Environment	R - D - O - U
International Wave Workshop Series	R - D - O - U
International Wave Modelling Group (WAM)	R - D - O ~ U
Ad Hoc - Mostly between individuals	R - D
	D - O
	O - U
	Not R - U

Desired

Better linkages between wave and other modellers (e.g. wave-ice, wave-current, wave-atmosphere)

Specifically better linkages should be established between wave modellers and CMC/RPN

NESS-type linkage is also a good prototype for similar large modelling projects which produce engineering results

CONSTRAINTS TO THE IMPLEMENTATION OF OPERATIONAL MODELS

Computer cycles and personnel resources to operate

Don't know how to assimilate satellite information - wind, waves, coupling

Don't know how to assimilate conventional surface information

Availability of appropriate input data in real time

Availability of appropriate related data - ice, current, bathymetry, sediment

Verification data

High Quality wind analyses and model output

PRIORITY AREAS OF RESEARCH FOR WAVE MODELS

Presently Supported

Techniques for assimilation of satellite SAR information into wave models (winds, waves, coupling)

Verification of remote sensing techniques (satellite, radar, etc.)

Provision of working operational models

Techniques for surface wind field analysis and forecasting (especially to T + 24 which NEB feels is presently inadequate)

Techniques for wave-current interaction

Techniques for shallow water

Techniques for erosion storms (from waves only, not currents)

Interactive, workstation-based wind/wave analysis and forecast system, including workstation WAM

Participation in WAM

New Initiatives and Priority

H Detailed analysis of the Halloween '91 EC "design busting" storm - example of the general need for analysis of the most severe storms - quantify error and uncertainty in hindcasts/forecasts

M Techniques for wave-ice interaction

M Techniques for surf zone analysis

M Analysis of trenching, infill, liquefaction, overtopping

M Global change impacts on design criteria

M Extremal analysis

H Updating of hindcast for design, especially to incorporate the very severe storms of the past 5 years, and to get us to the point where we have a routine updating procedure (PACWAV)

H Provision of appropriate data in real-time, especially satellite (including not only SAR but Scatterometer and Altimeter, which are not presently included in CSA plans)

H Techniques for assimilation of Scatterometer and H Altimeter data into wind and wave models

CURRENT MODELLING

Chairman: Jim Elliott, Bedford Institute of Oceanography

Rapporteur: Brian Petrie, Bedford Institute of Oceanography

SUMMARY
RESEARCH, DEVELOPMENT AND OPERATIONAL USE OF CURRENT MODELS

A review was made of oil spill trajectory models, current models, and wave models to provide a synopsis of present capabilities in Canada. The review focused on operational needs, the present status of operationally-oriented models, ongoing and planned research and linkages between the operational, development and research communities.

The review provides general information on model components and expected performance; it was not intended to provide detailed technical specification concerning model parameterization or physics. The important components of the models were reviewed for the purpose of providing an overall indication of capabilities, rather than to provide a basis for selecting operational models for given applications.

The purpose of the review was to serve as a discussion paper. It is anticipated that it will be used by interested parties to develop their own recommendations pertaining to future research and model development.

Reference: Godon, A., D. McGillivray and D. Dickins. 1991. Status: Research, Development and Operational Use of Ocean Models. Prepared for the Panel on Energy Research and Development by D.F. Dickins Associates Ltd. and the MEP Company Ltd.

BACKGROUND

The Panel on Energy Research and Development (PERD) undertook a study to evaluate the direction of research efforts required to provide effective oil spill trajectory, current and wave models for operational use. The following sections summarize the results of the current model review. Further detail is available in Godon *et al.* (1991) which is included as an Annex to these proceedings.

While the review was intended to be comprehensive, it was acknowledged at the outset that time and budget considerations would potentially constrain this objective. However, it was felt that the results would provide a useful foundation upon which to build during the Workshop. At that time, comments and additions were solicited from Workshop participants. These have been compiled and follow the summary.

The review included an examination of communications linkages between researchers, developers, operators and users of models. The objective of this aspect of the review was to identify deficiencies in existing linkages in order to improve future mechanisms whereby research efforts can lead to more effective operational products.

For the purposes of the review, an "operational model" was defined as a numerical prediction system which processes forecast or observed inputs to compute output forecast products such as ocean current trajectories. Models which were considered potentially operational were defined as "operationally-oriented". To be classified in this manner, a model would not presently be in regular use, but would have been designed and tested to run in a realistic operational setting.

CURRENT MODELS

Operational users of current models range from active users of ocean current forecasts to resource management users requiring models to understand fish migration and recruitment. Operational

current models provide current information for search and rescue, and oil spill trajectory, sea ice and iceberg drift models. The needs of various operational users are summarized in Table 1.

Table 1
Current Models: Operational Users

Users	Desired Model Output
DND Rescue Coordination Centres	Trajectory models for search and rescue.
Oil and Gas Industry	Current profile for impact on drilling riser and dynamically positioned vessels, search and rescue.
DFO Fisheries Management	Tidal and residual currents.
Marine Transportation, Fishermen, and Boaters	Tidal currents and hazards.
Application to Oil Spill Trajectory Models	Surface currents (top 1 m).
Application to Iceberg Drift Models	Surface and current profile.
Application to Sea Ice Drift Models	Residual surface current.

CURRENT MODEL CHARACTERISTICS

On the continental shelf, currents are a function of external forces (meteorological, tidal, surface gravity waves), internal forces and steering (density stratification, coriolis effect), boundary layer effects (shoreline geometry, bottom topography), and bottom friction.

Models can be classified according to the dimensions and types of effects modelled. Two dimensional barotropic models assume that the lines of equal pressure and equal density are parallel and that the water mass moves in one layer. Barotropic models which include some depth effects are often called 2 1/2-dimensional models. Three-dimensional baroclinic models describe currents that move through the vertical layers and thus account for all of the effects listed above. Baroclinic models are required in areas where density stratification is significant.

The computational requirements of current models vary considerably. Models have been implemented on platforms ranging from micro-computers to CRAYs. While typical model output consists of current vector plots, some systems are capable of terminal information display as well.

OPERATIONAL CURRENT MODELS REVIEWED

The review identified few ocean current models in regular use in Canada, although several operationally-oriented models were identified during the review. A summary of their features is presented in Table 2.

Table 2
Summary of Operational and Near Operational Current Models

Model	Primary Purpose	Input Data	Model Type	Limitations	Configuration	Output
BARO-2D ASA Consulting Ltd.	storm surges, iceberg impact risk, oil spill models	winds, tidal constituents boundary cond.	finite difference, up to 3000 elements	barotropic	Cray2, Cyber, PC	printouts and plots (DISPLA post processor
CANSARP Seaconsult	search & rescue all Canadian waters	CMC dial-up files of wind observations, time & date	2-D, internal residual current database, includes tidal model Juan de Fuca & Georgia Strait	shoreline scale is coarse	Sun Spark workstation	trajectory maps wind field maps
DRIFTCALC Seaconsult	search & rescue Juan de Fuca & Georgia Strait	winds from wind stations, time & date	2-D, internal residual current database, includes tidal model	spatial resolution too low for back eddies	PC based menu, mouse interface	trajectory maps, 4 corners of search area
LAYERS ASA Consulting Ltd.	thermal effluent, water quality	winds, tidal constituents, boundary cond.	finite differences horz. and vert. 2-3 layers, up to 3000 elements	barotropic	PC	printouts and plots, animated display
DCS BIO and The MEP Company	oil spill trajec. search & rescue	CMC wind & pressure, temp. tidal constituents, density	2 1/2-D with background current boundary condition & tidal forcing 8'8' lat/long grid on Scotian Shelf	barotropic, not easily moved to new locations	mainframe with link to CMC	maps of current vectors, current profiles, variable resolution
Tidal models Mike Foreman, Falconer Henry IOS	tidal currents	bathymetry shorelines tidal heights at boundaries	2-D, barotropic, 10 constituents variable, triangular FE grid	tidal prediction only	mini-computer: Reliant FX-40	maps of current vectors, variable resolution
TideView IOS & Channel Consulting	tidal currents Juan de Fuca & Georgia Strait	time & date	2-D, barotropic, 8 constituents used for reconstruction, based on a variable, triangular FE grid	tidal prediction only	PC based, menu & mouse driven	2 day tidal heights, tidal currents
TIM ASA Consulting Ltd.	sediment transport	winds, stratification, tidal constituents, boundary cond.	3-D, finite difference horz., Galerkin method vert., 10 basis functions, up to 5000 elements	unknown	Cyber, VAX,PC	printout and plots (HP or Calcomp)
2.5D-MULT ASA Consulting Ltd.	mean circulation for sea-ice models	winds, local vert, profiles, boundary cond.	finite difference horz., Galerkin method vert., 20 km resolution on Labrador Sea and Grand Banks	tides not presently implemented	HP 1000, PC	printout and display post-processor

Of the models reviewed, all but one were barotropic. The TIM model developed by ASA Consulting Ltd. is a three-dimensional baroclinic model.

CURRENT MODELLING RESEARCH

Current modelling research is being done at various institutions across Canada to address regional issues. On the West Coast, research models to predict residual and tidal currents are under active development at the Institute for Ocean Sciences. Work has recently started in Quebec to develop models for the St. Lawrence River estuary and the Gulf of St. Lawrence. On the East Coast, present efforts focus on the Grand Banks region.

The general objectives of the research being conducted in all regions is to satisfy the need to understand fish migration patterns, and provide current data to oil spill trajectory models. The research efforts currently under-way or planned in Canada are summarized in Table 3.

Table 3
Current Models: Research Efforts

Organization	Research Areas
Bedford Institute of Oceanography C. Anderson	Setting up the Operational Current Modelling System (OCS) on the Grand Banks, implementing multi-constituent tidal forcing.
D. Greenberg and J. Loder	Finite element modelling techniques running research models within a PC environment.
Institute of Ocean Sciences B. Crawford	Residual current models of B.C. waters.
M. Forman	Two dimensional tidal models of B.C. waters.
Memorial University of Newfoundland R. Greatbacht	Two and three-dimensional shelf models for the Grand Banks and North Atlantic.
Insitut Nationale de la Recherche Scientifique V. Koutitonsky	Three-dimensional model of the St. Lawrence estuary.

OPERATIONAL/RESEARCH LINKAGES

Linkages between operations and research groups were studied with an interest in identifying areas where the operational utility of models could be enhanced through improved communications, or better information transfer. Through the review, it was found that while linkages could be identified between researchers, model developers, model operators and users of model output, the strength of these linkages varied.

For current models, most Canadian research and model use is carried out by groups within the same department (Fisheries and Oceans Canada) and strong linkages have been established within the department. Fisheries and Oceans also has developed a formal mechanism for technology transfer to Canadian industry coordinated by Industrial Liaison Officers at various research institutions.

Internationally, the World Ocean Circulation Experiment (WOCE) provides a forum for exchange of information and modelling techniques.

WORKSHOP RESPONSE TO THE OCEAN MODEL REVIEW
CURRENT MODELLING COMPONENT

A review of operational and research ocean models was prepared for PERD (Status: Research, Development and Operational Use of Ocean Models by D.F. Dickins and the MEP Company) for distribution and comment at this Workshop. While the full review is attached as an appendix to these proceedings, comments from Workshop participants pertaining to the review are noted here.

COMMENTS CONCERNING THE STATE OF THE ART REVIEW

The following comments are confined to the current modelling aspects of the report.

p. B-22 No mention is made of the difficulty of verifying the surface current models; is CODAR a possibility?

While user-friendly models may be desirable, I do not think that the researchers should be required to create them; consulting firms, interacting with the researchers who develop the models and the users, could do a better job. However, I would like to see DFO develop the capability of easy access to and use of their models so that quick response to outside requests for information was possible.

p. B-24 The statement that the OCS model "has proven to be capable of accurately predicting surface currents" (followed by 5 references) appears to be without foundation based on the reports at this meeting. No comprehensive validation of the model has been conducted.

p. B-26 This is not meant to single out one particular model but the Halifax Harbour model has some very special input requirements that could make its use as an operational model improbable. This is an example of how a review, done very quickly, can fail to screen out models unlikely to see operational use. Furthermore, some models (listed in the rapporteur's summary) which could be readily used in operational models were missed.

p. B-31 The list of models is incomplete. See the following additions.

ADDITIONAL RESEARCH MODELS

Several research models were noted as missing from that review document including:

Model	Status	Description	References
Residual Circulation Model (Tee; BIO)	Model available for research	• 3-D numerical tidal model • 41 levels in vertical column • utilizes a 2-D depth-averaged nonlinear tidal model to first compute depth-averaged tidal current • developed for area SW of Nova Scotia	Tee, 1976; Tee, 1987; Tee et al., 1988
Western Bank Model (Thompson; Dalhousie University)	Under development	• shelf current model (inertial) incorporating internal measurement of currents and sea level using adjoint methods of data assimilation • goal is to use the data to infer flow across open boundary conditions and in this way derive nowcasts and short-term forecasts (1-2 days) of the surface flow • prototype will be tested on the Western Bank in April, 1992	Thompson, in press
Inertial Current Model (de Young; MUN, and Tang; BIO)	Model available for research	• two-layer, 1-D model for simulation of inertial currents • input consists of wind motion (u and v components of wind stress) • model developed and tested against current measurements on the Grand Banks	de Young and Tang, 1988
Grand Banks Barotropic Mean Flow Model (Greenberg and Petrie; BIO)	Model available for research	• 2-D, vertically averaged model • developed for the Grand Banks • driven by specified sea level gradient at the northern boundary • comparison with available current data shows good qualitative agreement with general flow patterns	Greenberg and Petrie, 1988
Grand Banks Barotropic Storm-Forced Model (Petrie; BIO)	Model available for research	• 2-D, vertically integrated • linear but with nonlinear bottom friction • developed for Grand Banks with approximately 1000 by 1500 km domain • requires 2-D meteorological stress field (time and spatially dependent • free surface boundary conditions • development work to make model user-friendly	Petrie and Szabo, in press

Additional current model research is under-way at the Northwest Atlantic Fisheries Centre in St. John's, NF. Two specific models, a Northeast Newfoundland Shelf Model, (J. Helbig) and a Northeast Newfoundland Tidal Model (S. Narayanan and D. Greenberg, BIO) are presently under development.

At the Institute of Ocean Sciences in Sydney, BC, a research model developed by P. Budgell for the Beaufort Sea has also recently been applied to research in Hecate Strait.

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SEARCH AND RESCUE PLANNING

(Abstract Only)

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In determining search areas it is imperative that the Marine SAR Controller have the tools at hand to quickly determine an area of high probability in which survivors of a marine incident will be located under varying climatic conditions. In addition we need to do these predictions for various scenarios such as a person in the water or in a raft or lifeboat. Obviously each scenario presents different variables to be factored into the model such as sea current and leeway influences. Until the early 80's, the Controller had to rely on manual time consuming calculations based on data and formulae developed by the United States Coast Guard. In the early 1980's, Controllers were supplied with a program which carried out these mathematical functions and provided graphical results, a vast improvement on old practices. Unfortunately the system was not user friendly which hampered its acceptance.

Presently Canadian RCC's are conducting trials on new computer software designed by Seaconsult Ltd., which operates on a Sun Workstation. This new system will replace similar software developed by the same company. Presently the system is not user friendly enough for operational requirements.

REGULATORY REQUIREMENT FOR CURRENT MODELLING

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Enabling regulatory legislation such as the Oil and Gas Production and Conservation Act, the Arctic Waters Pollution Prevention Act and the Environmental Assessment Guidelines Order mandate the regulator (National Energy Board and its sister agencies Canada- Newfoundland and the Canada-Nova Scotia Offshore Petroleum Boards) to ensure that offshore operations are conducted with all due regard for the safety of personnel, the operation, and the environment.

To carry out these responsibilities, the regulator has available several means such as the Environmental Assessment review and Regulatory approvals processes prior to commencement of offshore activities, inspections and monitoring once an activity is under way, and post project review on termination of an activity. Also, the regulator may initiate, support and manage R&D that will assist in the development of an equitable regulatory regime and efficient, environmentally safe operating systems.

During the Environmental Assessment and Regulatory Approvals processes, the regulator needs to consider the physical environment conditions for the area of proposed operations prior to approving operations. One of the important physical parameters considered is ocean current including its strength, direction, and spatial and temporal distribution.

SAFETY OF PERSONNEL AND OF THE OPERATION

Since historical ocean current data bases are generally inadequate, ocean current data bases may need to be supplemented by ocean current model data to provide an acceptable measure of the parameter. The parameter may then be used to determine if the proposed drilling or production structure meets the design and operational limits requirements for operation in the designated area.

Environmental design criteria (maximum environmental loads) determine the suitability of a structure or equipment in terms of survivability. One piece of equipment that is sensitive to maximum ocean current forces is the marine riser. Current models are useful in defining transitory current (solitons) loads to determine the suitability of this equipment.

Operational limits (response to more frequently expected loads) determine the suitability of a structure in terms of operational safety and efficiency. In the case of moored structures, adequacy of the mooring systems will be checked. For sea bottom based structures, current models may be used to assess design load forces, sea bed stability, and potential for significant scour.

For Search and Rescue planning during the review stage, ocean current models may be required to determine the type and deployment of SAR resources. During the operational stage,current models may be used in conjunction with current measurements to plan rescue operations.

PROTECTION OF THE ENVIRONMENT

For longer term installations such as production facilities, regulations may require an Environmental Protection Plan. Current modelling data may be needed to assess adequacy of mitigative strategies and to develop scientifically credible environmental monitoring programs.

Used in conjunction with oil spill trajectory models, ocean current models are required to identify priority response areas for contingency plans and for planning the disposal of countermeasure resources. They may also be used to pre-determine the efficacy of given countermeasure systems for the proposed area of operations.

OPERATIONAL SUPPORT

For ice/iceberg management during the planning/regulatory review stage, ocean current models may be required to determine operating seasons and requirements for ice management resources. During operations stage, in conjunction with iceberg/ice motion models, current models may be required to assist in establishing environmental alert status and to determine priority and method of ice management. Similarly, reliable operational models could be used in support of diving operations which are sensitive to strong currents.

RESEARCH PRIORITIES FOR OCEAN CURRENT MODELS A REGULATORY PERSPECTIVE

In support of the environmental assessment and regulatory approval processes for oil and gas activities in the offshore, ocean current modelling in the following areas would be useful:

- Development of new generation baroclinic models incorporating; topographic effects and hydrodynamic instabilities for ocean eddies, upwelling, and wave/current interaction.
- Development of model validation methodology and data bases.
- Assimilation of remotely sensed data into research and operational current models.
- Development of reliable user friendly operational models that provide reasonable guidance for lead times of 12-24 hours.
- Application of current models to subsea erosion and scour.
- Application of current models to current/structure interaction.

CURRENT MODELLING

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ABSTRACT

The oil and gas industry needs accurate hindcasts and operational forecasts of ocean currents to insure the safety and efficiency of its offshore activities. From a research perspective, this requires modelling the combined response of the circulation to the dominant forcing mechanisms on the continental shelf: tides, winds, buoyancy inputs and offshore currents and eddies. Barotropic models for the depth-averaged current are generally well-calibrated for the tides and give reasonable agreement for the mean flow and subtidal response to wind. Furthermore, the so-called 2½-D models (barotropic coupled with a local 1-D current profile) produce good estimates of the friction-induced shear in weakly-stratified waters, but do not provide accurate representations of the baroclinic circulation. Idealized models for the internal tide generated by the barotropic flow over weak topography do produce realistic baroclinic responses in stratified seas, including the extreme currents (1-2 m/s) and vertical shears associated with short internal wave packets. Similarly in the inertial band, analytical wind-driven models give reasonable representations of the current in simple situations (eg. flat-bottom, open shelf, two-layer stratification), but cannot simulate complex 3-D circulations in the coastal zone or over rugged bathymetry. The buoyancy forcing mechanisms and the dynamics of waves and eddies in energetic flows such as the Labrador Current are also poorly understood.

Future modelling efforts should be directed toward improved model resolution of coastline and bathymetric irregularities and improved representations of the baroclinic components of the flow. For fully 3-D baroclinic circulation over finite-amplitude bathymetry, primitive equation models are required to obtain realistic statistics and spatial distributions. New techniques for data assimilation must also be developed for constraining and improving operational forecast models. The benefits of assimilating satellite altimeter and sea surface temperature data have been demonstrated in certain deep ocean modelling efforts, but its value for continental shelf models is questionable with present levels of accuracy.

INTRODUCTION

The needs and goals of the offshore oil and gas industry for current modelling, as expressed by the PERD priorities, are slightly different from those of the research community. From the PERD perspective, the primary requirements are for 1) realistic estimates (and associated uncertainties) of current means and extremes for design studies, and 2) timely estimates for use in operational forecasts. The role of research, on the other hand, is to develop and evaluate models with a view toward understanding the basic physics and dynamical interactions underlying the results. This activity often requires the formulation of very simple models to isolate and study specific processes, as opposed to the development of complex numerical models for the general circulation.

To obtain realistic estimates of currents requires modelling the responses to the dominant forcing factors on the continental shelves: tides, wind, buoyancy input, and offshore currents (or,

more generally, boundary mass fluxes). For operational purposes, the present state-of-the-art for both hindcasting and forecasting of currents consists primarily of 2-D (depth-averaged) barotropic models and 2½-D models, which include a 1-D calculation of a current profile consistent with surface and bottom fluxes but do not have full baroclinic dynamics. In addition, some idealized baroclinic models provide realistic results (as well as insight) in certain settings, but their application is restricted by the degree to which the underlying assumptions are satisfied. Some of these models will be briefly reviewed below, followed by some recommendations for future research initiatives. Examples are drawn primarily from PERD-sponsored research, but the conclusions are not based solely on those results.

PRESENT STATE-OF-THE-ART

Barotropic models have been developed to simulate the long-term mean flows in the Gulf of Maine (Smith, 1983) and on the Newfoundland Shelf and Grand Banks (Greenberg and Petrie, 1988). Both models are driven by a sea level set-up on the cross-shelf "backward boundary" (through which free shelf waves would propagate into the domain), and by topographic rectification of the M_2 tide in the case of the Gulf of Maine. Model results compare well qualitatively with measurements of the depth-averaged mean current in both regimes (Figure 1), and the comparison is even quantatively accurate for several areas on the Grand Banks. However, near the rugged topographic features of the Gulf of Maine (e.g. Browns Bank), the model underestimates the depth-averaged current by factors of 2 to 4. This shortcoming has been attributed to: a) relatively coarse resolution of the bathymetry (which leads to misrepresentation of the tidal rectification), and b) the absence of the steady baroclinic flow component. The latter problem is of general concern in most regions of the eastern continental shelf. With regard to atmospheric forcing, the effects of a steady or seasonal wind stress (see Wright, et al, 1986, for example) may be added to the above solution on the presumption that its magnitude is small relative to the dominant components of the flow.

Another success of the barotropic model is in the simulation of the surface tides on the continental shelf. The M_2 tide on the Scotian Shelf, for instance, is well-calibrated by sea level and subsurface pressure observations from the boundaries and interior of the domain. The tidal excursions (Figure 2; de Margerie and Lank, 1986) indicate maximum currents on the western end of the shelf, due to near-resonance on the Gulf of Maine/Bay of Fundy, and also large currents over the shallow outer banks of the Shelf.

Related to the strong tidal flux at the shelf edge are groups of large-amplitude internal waves, which are generated primarily by the semi-diurnal flow over topography, and whose surface signature of long alternating rough and smooth bands is revealed by SLAR images (Figure 3). The M_2 forcing function for these waves depends upon the strength of the barotropic flow and the bathymetry (Figure 4), as well as the local stratification. For two-layer stratification that approximates that of the Scotian Shelf in summer, a simple 2-D baroclinic model (Sandstrom and Quon, in prep.) indicates that internal waves with amplitudes of 30-60 m and opposing currents in the top and bottom layers of order 0.5 m s^{-1} are generated on every tidal cycle. Nonlinearities and dispersion cause the formation of packets of short-crested waves, with space and time scales of 100 m and 10 min., that propagate with significant energy over distances of order 10 km at speeds of order 1 m s^{-1} . The intense currents and vertical shear associated with these waves are of great interest to operators in the vicinity of strong topographic features. However, their predictability somewhat limited by incomplete knowledge of the stratification and the fact that the generation process depends upon the net flux over topography, not just the M_2 component of it. Nevertheless, current surge forecasts based on the two-layer baroclinic model with tidal forcing (Figure 4) would be reasonably accurate and useful operationally.

Wind-driven variability on the continental shelf occurs at three distinctly different time scales: subtidal (periods of 2-10 d), inertial (17 hr), and surface wave (2-20 s). Barotropic models have shown reasonable success in simulating subtidal currents, but the inertial current response is fully baroclinic and involves more complex dynamics. As an example of subtidal simulation, Petrie and Szabo (in prep.) have modelled the responses on the Grand Banks to 32 of the most severe storms in the 34-year period, 1951-84 as part of the Mobil Extreme Storm Climatology. During five of these storms, there were current meters in place in the Hibernia region that could be used to validate the model results. Intercomparisons for those five events indicate that the model worked well on two occasions, poorly on two and the other result was mixed. Storm 25 was characterized by a strong southward wind stress pulse of nearly 3 Pa (Figure 5a) which produced a westward current pulse of 0.5 m s^{-1} in the model (Figure 5b). This behaviour is closely reflected in the observations (Figure 5c). However, other intercomparisons (e.g. Storm 28,29; not shown) showed qualitative disagreement and/or masking of the subtidal response by the inertial response. Nevertheless, in terms of the statistics of extreme currents and design loads, such hindcast model results are useful in quantifying the subtidal component of the response to wind.

The inertial response to mesoscale features in the wind field is very difficult to model operationally because: 1) the mesoscale structure of storms is not well known, and 2) the response itself is sensitive to a variety of factors such as the stratification, the presence of a mean current or the presence of a coastal boundary. Nevertheless, the recent 1-D baroclinic model of DeYoung and Tang (1990) shows reasonable success in producing realistic inertial currents under conditions which satisfy the model assumptions (2-layer stratification, flat-bottomed open shelf, steadily translating storm of moderate scale). In these situations, the response is purely baroclinic, provided the storm translation speed lies between the propagation speeds of the free barotropic and baroclinic inertial modes. In an inertial hindcast for the Hibernia region in the fall of 1986 (Figure 6), the model was tested against observed currents during the passage of three distinct storms of moderate scale (Figure 7). The results (Figure 8) showed very good agreement for the first two storms, and slightly poorer agreement for the third (probably because of its sharp change in direction on day 279). The maximum observed inertial response was of the order of 0.30 m s^{-1} and 180° out of phase between the upper and lower layers, which leads to very strong shears across the pycnocline. However, as mentioned above, the success of the model simulations is limited by the model assumptions, such that when there was no well-defined storm present, the inertial energy was not related to the local wind.

Finally, 2½-D models have been shown to give reasonable fits to current profiles in well-mixed waters (Tee et al, 1987) and show some success in estimating surface currents (MEP, 1988), but do not perform well in stratified waters with strong currents or wind forcing because of the lack of full baroclinic dynamics. The MEP OCS model, for example (Figure 9), was tested against current and drifter observations from the Scotian Shelf during the Canadian Atlantic Storms Program (Dec.1985-Mar.1986). Using CMC forecast and analyzed winds, the model was applied in both the hindcast and (simulated) forecast modes, and the results were compared against the trajectory of a single Hermes surface drifter (Figure 10) and against CODAR (HF groundwave radar) measurements of the surface current (Figure 11). While some of the discrepancies may be related to errors in the wind field, there seemed to be a clear excess of inertial energy in the forecast current relative to the observations. Furthermore, detailed comparisons at mooring sites further offshore show poor agreement, both qualitatively in terms of the vertical structure of the transient currents, and quantitatively in the magnitudes of particularly the deep currents. In summary, then, the 2.5-D models work well in well-mixed waters and achieve some success in simulating surface currents, but are severely limited by the absence of baroclinic dynamics. Also, their complexity may render them somewhat cumbersome and hence unsuitable in an operational setting.

FUTURE NEEDS

Several problems with existing current models are presently being addressed. For instance, the problem of properly resolving complex bathymetry has been accounted for in a new model for the circulation in the Gulf of Maine (sponsored jointly by GLOBEC and PERD) which features an easily adjustable finite element grid (Figure 12). This technique allows grid points to be concentrated in regions where the topography varies rapidly or where the fine resolution of the current field is particularly important. In addition, the GLOBEC/PERD model is addressing the need for some baroclinic dynamics by constructing diagnostic solutions for the seasonal density fields, which have been derived from a newly-developed climatological data base (Figure 13). The diagnostic calculations are considered to be a first step toward modelling the full baroclinic circulation, but initial testing of the solutions is encouraging.

The proper treatment of the full time-dependent baroclinic flow field over finite-amplitude topography requires the application of a primitive equation model. On eastern Canadian continental shelf, examples of such flows are the Labrador Current with its active eddy field along the shelf edge, and the Nova Scotian Current, particularly during the summer upwelling regime. A primitive equation model known as SPEM (Semispectral Primitive Equation Model; Haidvogel et al, 1991) has recently been applied to study the turbulent circulation of the California Current System off the US west coast (Figure 14). With substantial coastline irregularities and finite-amplitude topography, this model reproduces the realistic eddies and filaments ("squirts") which protrude offshore in response to bumps in the coastline. These patterns are confirmed in the surface layers by satellite SST and Lagrangian drifter observations. Furthermore, the current and density variances at 100 m from an 18-month simulation with this model (Figure 15) reflect this strong baroclinic behaviour and its influence by the geometry of the domain. While such models may not become operational in the near future, they are required to understand the complex interplay between baroclinic currents, wind stress and topography.

The development of sophisticated techniques for assimilating near-real-time data into circulation models is relatively new in the field of oceanography, but promises significant improvements in an operational setting with the advent of satellite and other remote sensing systems. The idea is to replace detailed knowledge of the model boundary and initial conditions with a systematic way to guide and constrain the model with real-time data. Recent notable successes have been achieved with the incorporation of satellite altimeter and infrared image data into open ocean models. One example of such a scheme is Ikeda's quasigeostrophic model (Figure 16; in prep.) for assimilating GEOSAT altimeter data over the Newfoundland Basin. In this method, altimeter data from successive satellite passes (separated by 3 days and 100 km) are used to "nudge" the model solution toward the observations. The results for the upper layer streamfunction show distinct evidence for propagation that cannot be discerned from the observations (Figure 17). This sort of dynamical interpolation is of great benefit in understanding and expanding knowledge of existing conditions in the ocean, and also in forecasting their future development.

CONCLUSIONS/RECOMMENDATIONS

Examination of the present state-of-the-art of ocean current modelling leads to the following conclusions and recommendations:

1) 2-D barotropic models provide realistic estimates of the depth-averaged current on weakly-stratified, open shelves in response to tides, wind and boundary mass fluxes. Higher resolution is required in regions of rugged bathymetry.

2) 2½-D models give reasonable vertical structure with strong friction and weak stratification, but lack full baroclinic dynamics characterizing strong ocean currents, inertial waves, etc.

3) Simple baroclinic models can give remarkably good simulations internal wave responses to wind and tide under certain sets of limiting conditions.

4) Future modelling efforts should be focused on:

   a) improved resolution of bathymetry and coastline through the use of techniques such as finite element grids,
   b) simulating full baroclinic dynamics for strong currents with finite amplitude bathymetry using primitive equation models, and
   c) development of data assimilation techniques, especially for the continental shelf setting.

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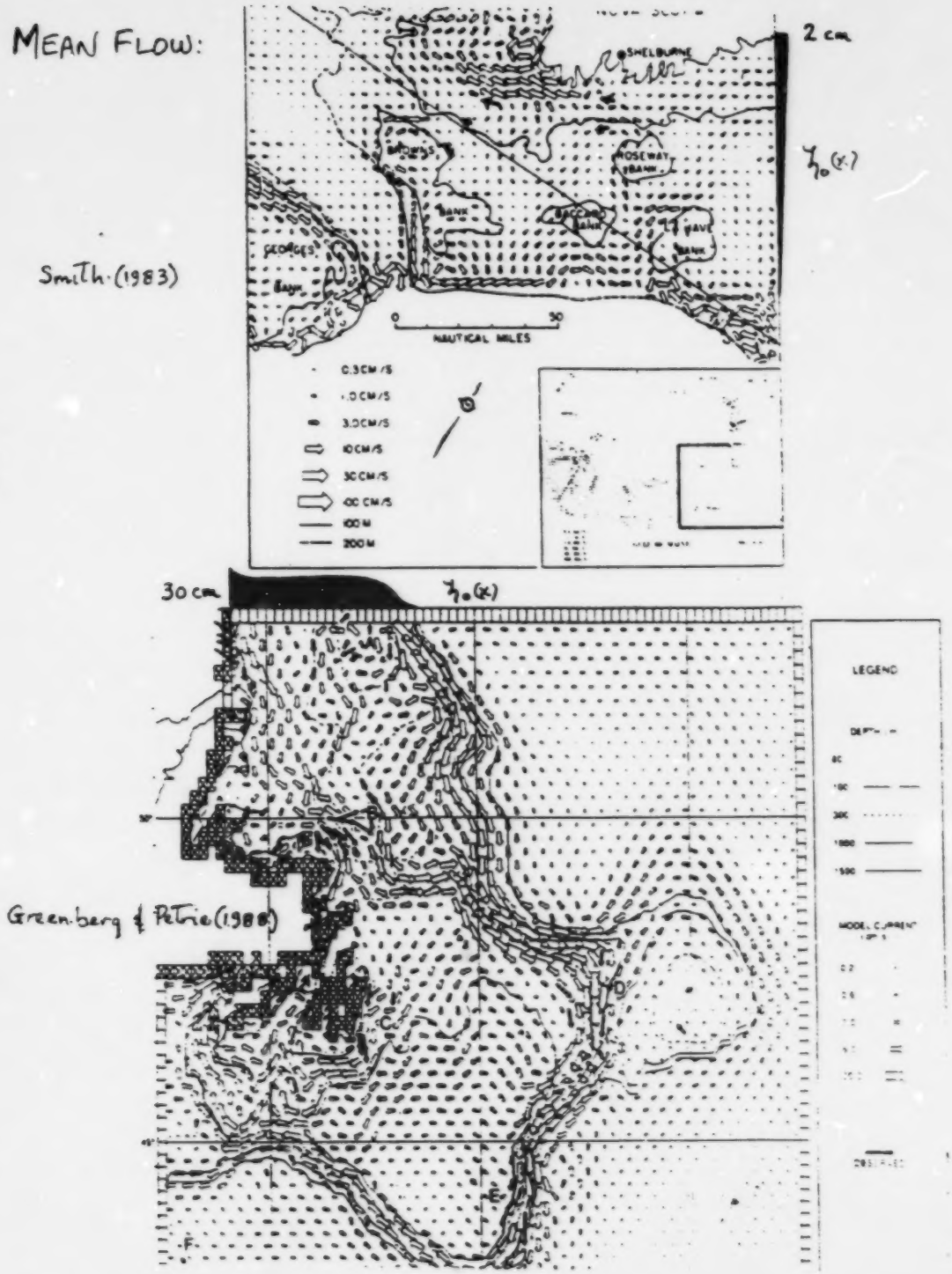


Figure 1. 2-D barotropic model simulations of the depth-averaged mean current field on: a) the western Scotian Shelf, and b) the Newfoundland Shelf and Grand Banks. The circulations are driven by inflows across the "backward" boundaries (see text) that are balanced by cross-shelf setups of sea level.

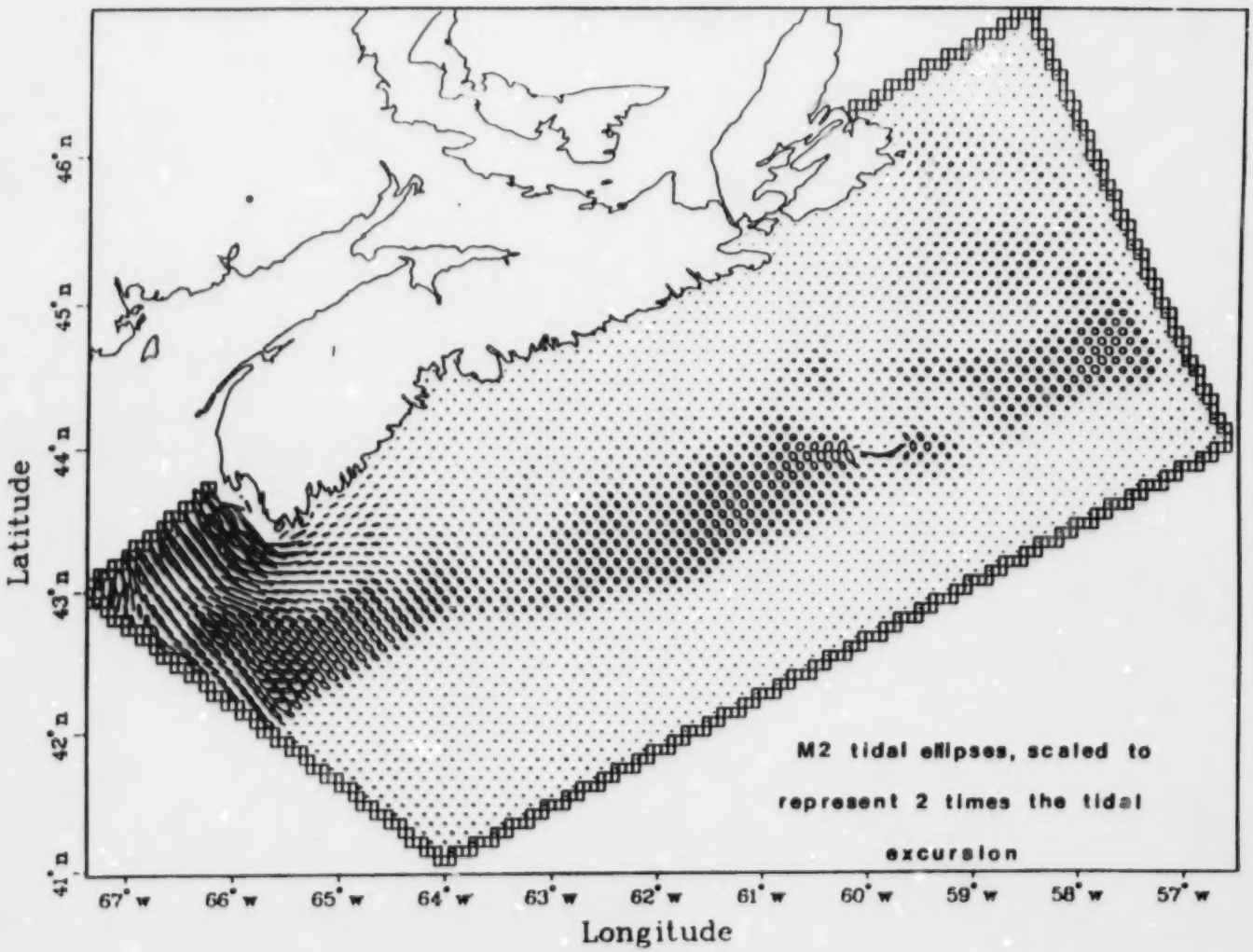


Figure 2. Model M_2 tidal ellipses for the Scotian Shelf (de Margerie and Lank, 1986).

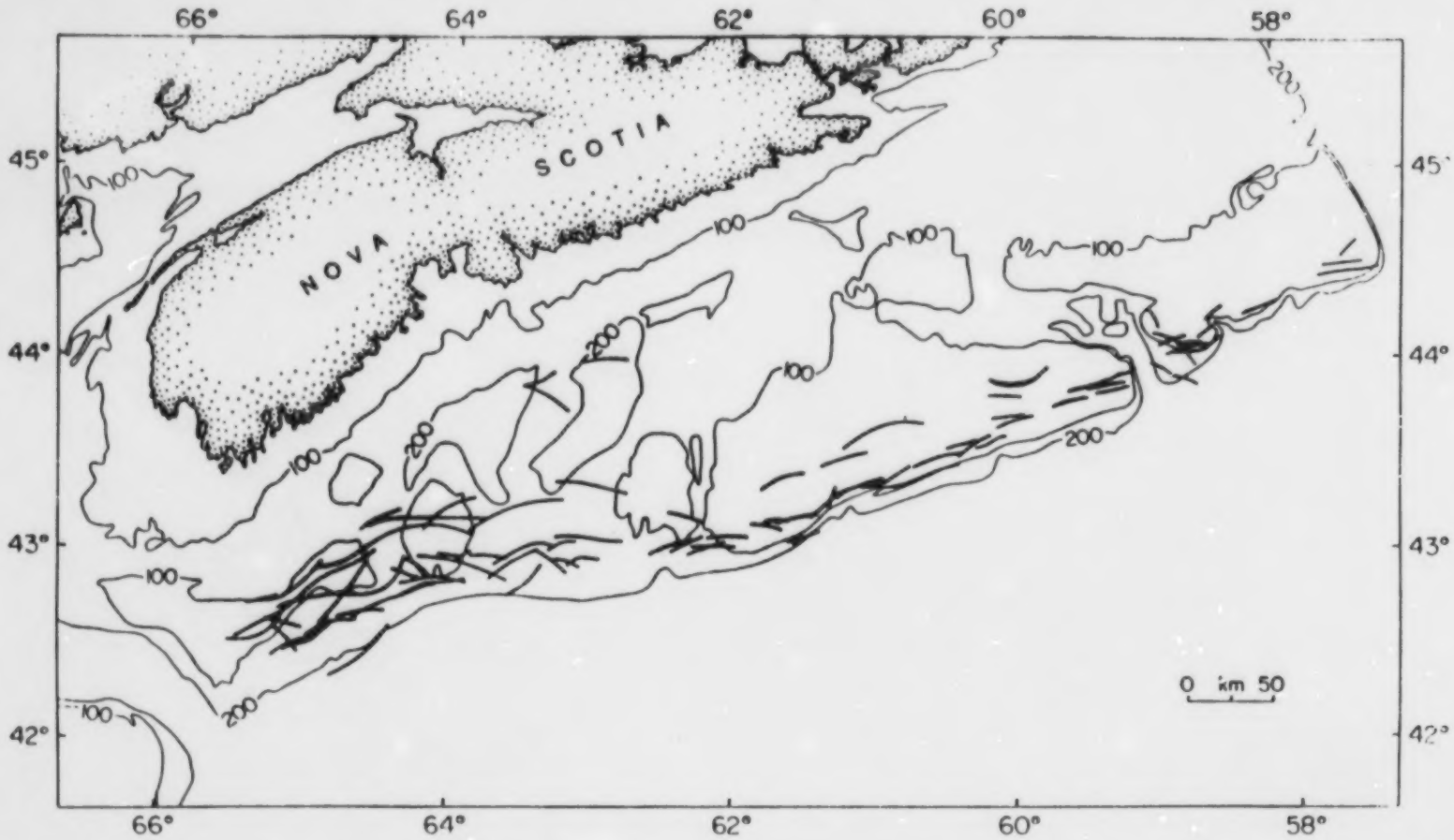


Figure 3. Surface signatures of large-amplitude internal waves near the Scotian Shelf break, detected by airborne SLAR measurements.

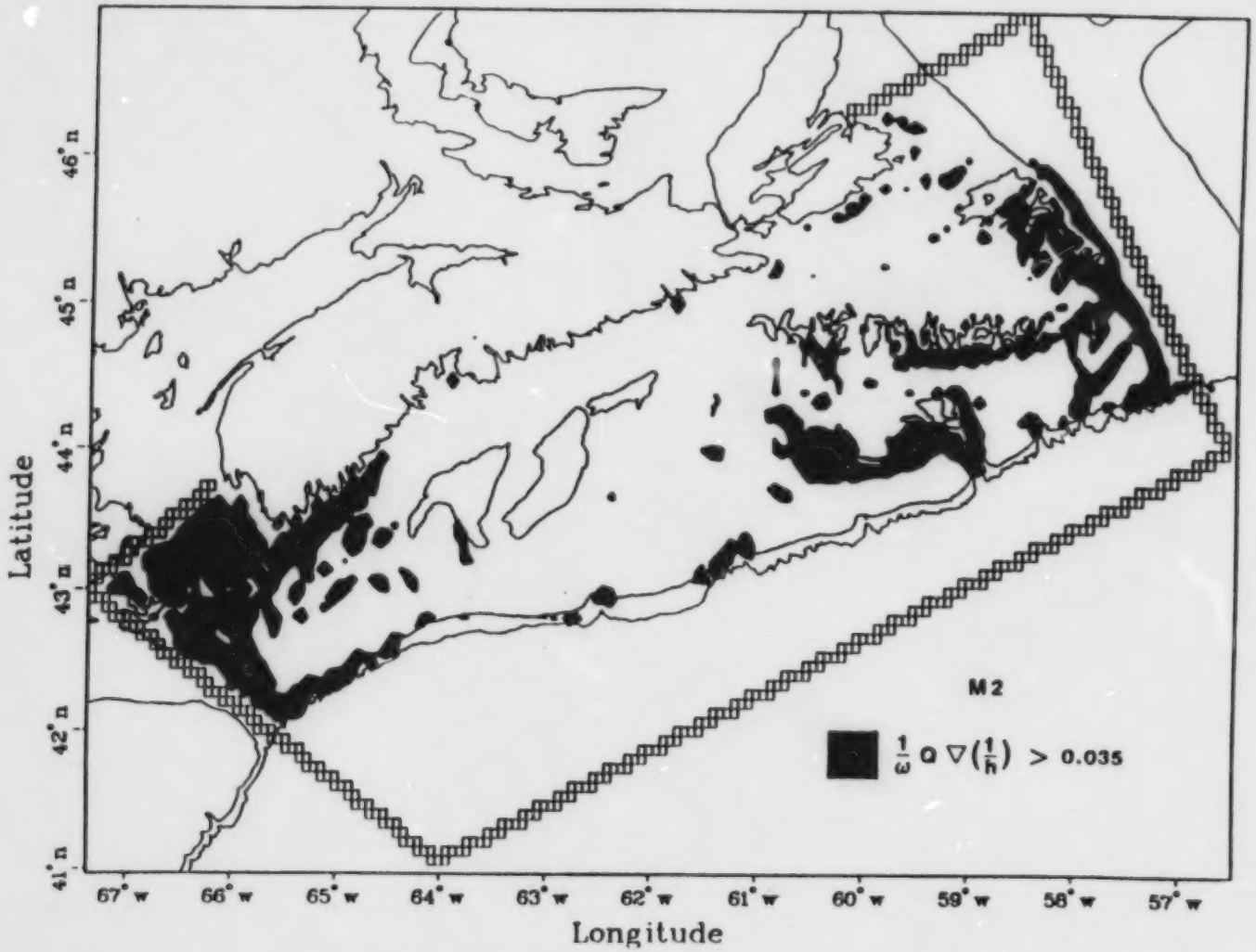


Figure 4. Bathymetric M_2 forcing function for large-amplitude internal waves.

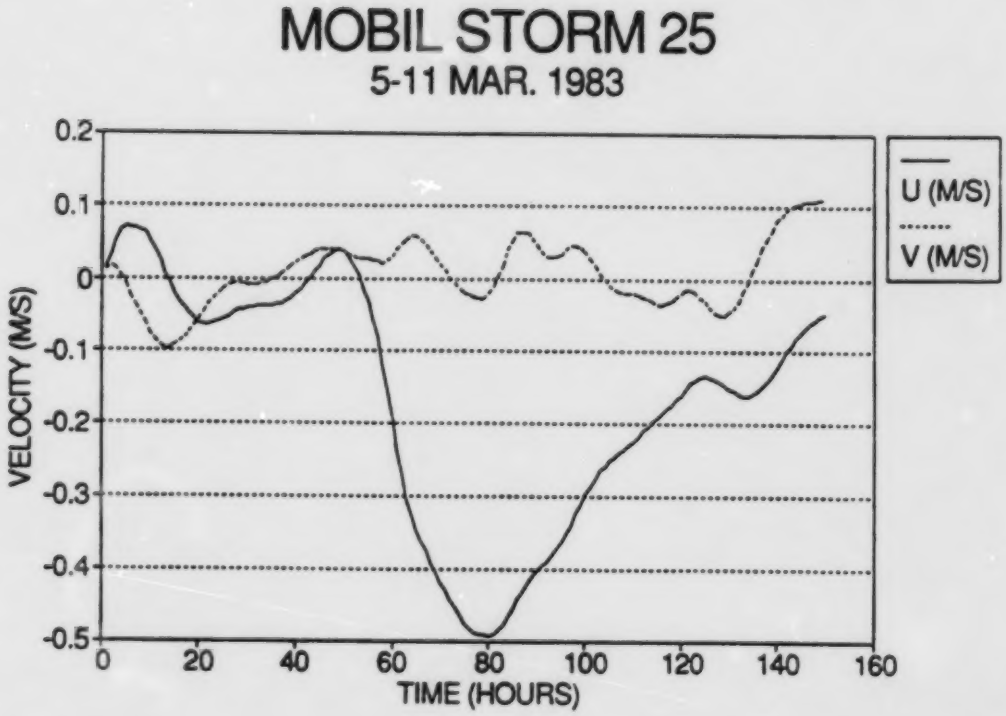


Figure 5a. Northward (TAUY) and eastward (TAUX) windstress components for Storm 25 of the Mobil Extreme Storm Climatology (Petrie and Szabo, in prep.)

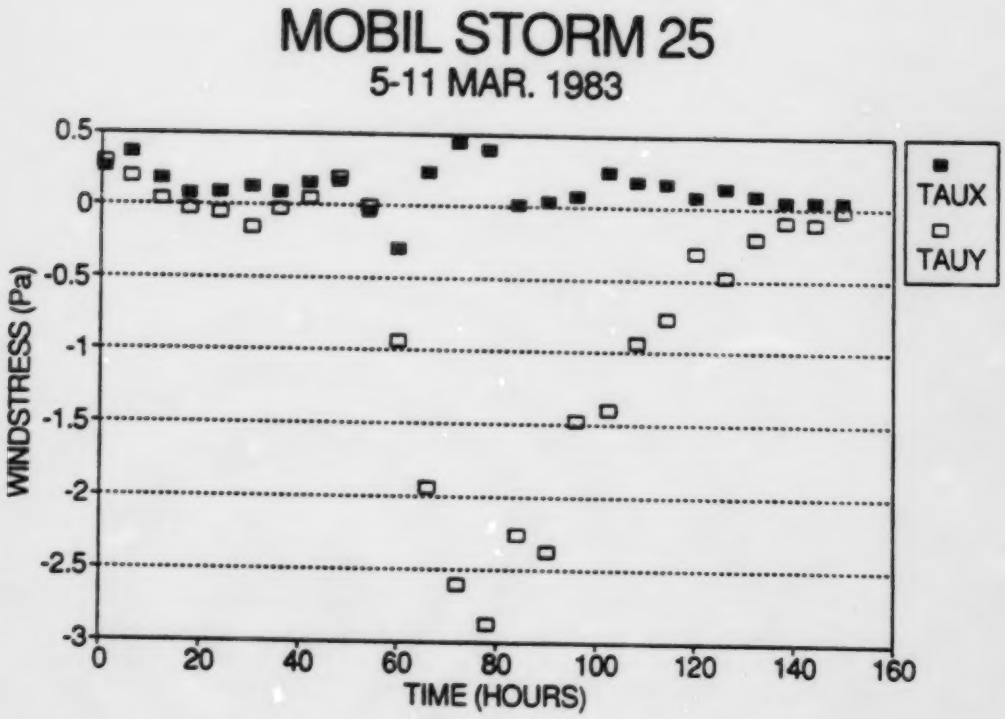


Figure 5b. Model depth-averaged northward (V) and eastward (U) current components near Hibernia during Mobil Storm 25

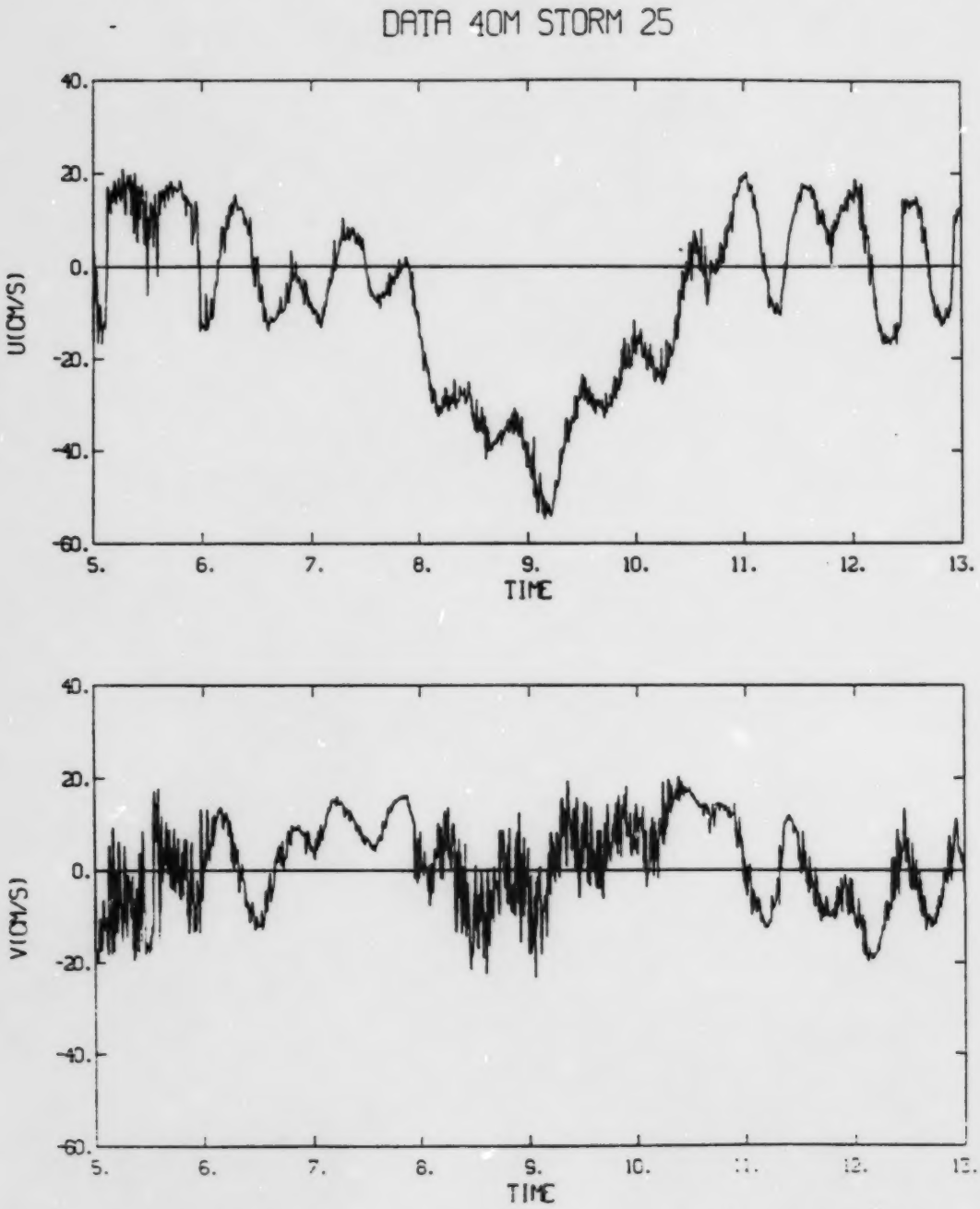


Figure 5c. Observed northward (V) and eastward (U) current components at 40 m depth near Hibernia during Mobil Storm 25

(a)

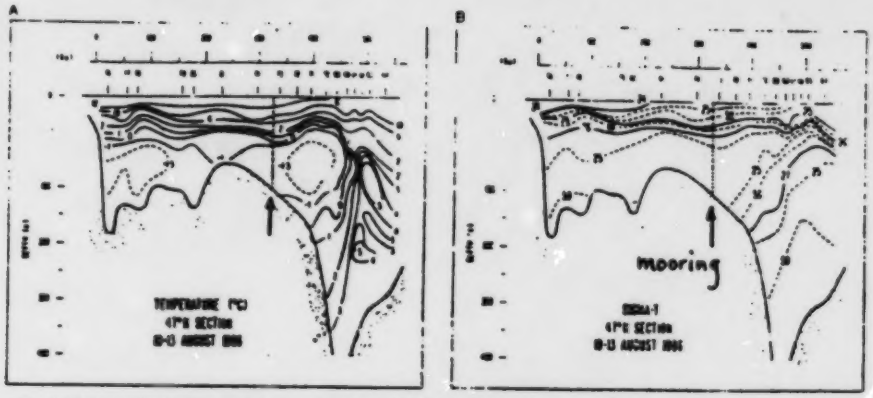


FIG. 2. Transect of (a) temperature and (b) σ_t along 47°N for 10–13 August 1986. The data were provided courtesy of S. Akenhead of the Northwest Atlantic Fisheries Center, St. John's, Newfoundland. The vertical dashed line indicates the mooring site.

(b)

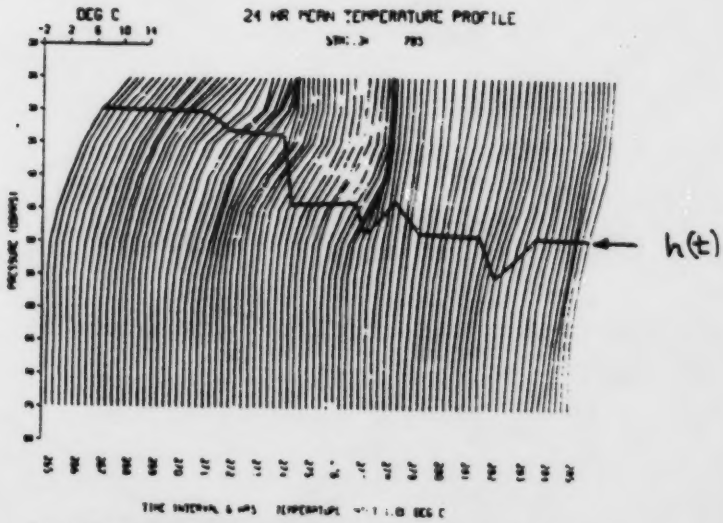


FIG. 11. The temperature profile as determined from the thermistor chain data. Each line represents a 24 hour average. The dashed line indicates the bottom of the mixed layer as determined from the maximum in dT/dz. Note that the mixed layer depth increases from day 270 onward reaching a maximum on day 281.

Figure 6. (a) Temperature and density sections along 47°N during 10-13 August, 1986. Vertical arrow and dotted line indicate mooring location.
(b) Daily mean temperature profiles from thermistor chain data at the mooring site. Dashed line approximates the base of the mixed layer as determined by the maximum vertical temperature gradient.

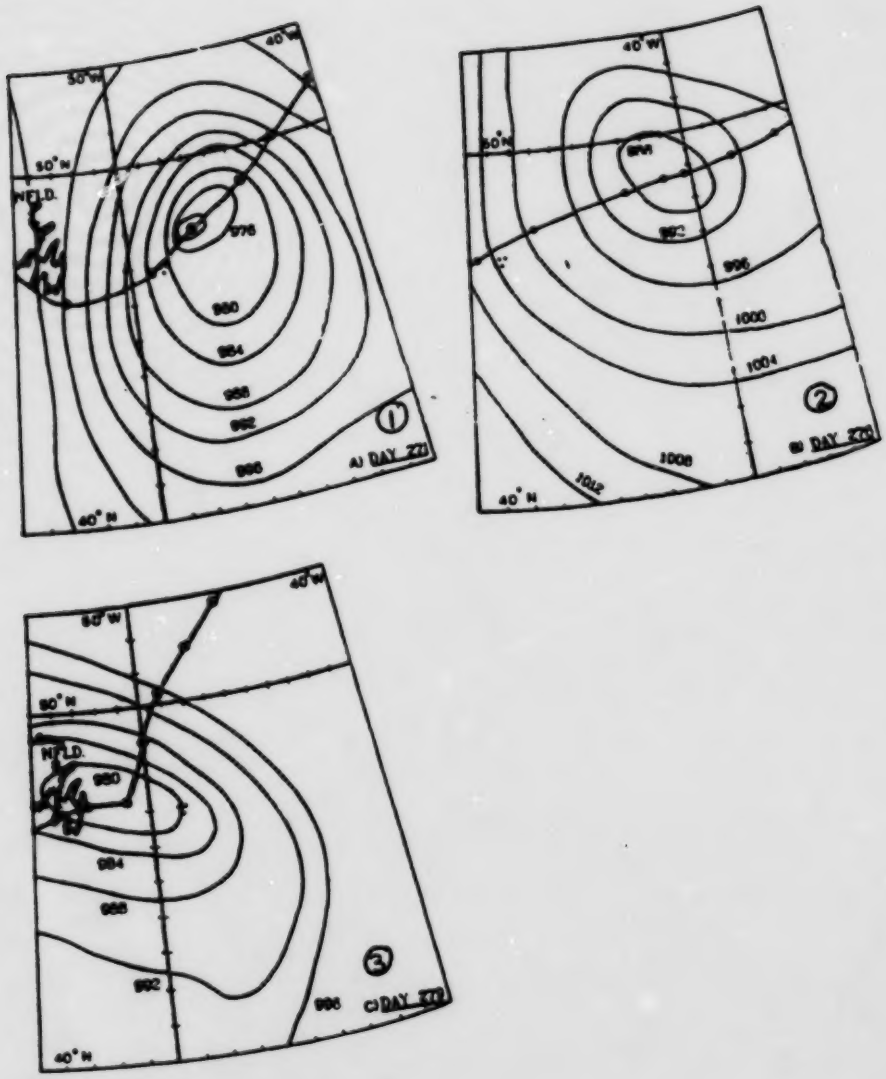


Figure 7. Surface pressure charts showing the progression of three storms that passed over the region during the latter portion of the mooring records. Heavy line indicates storm track with large dots every 6 hours. Small dots indicate triangular mooring array.

(a) FORCING:

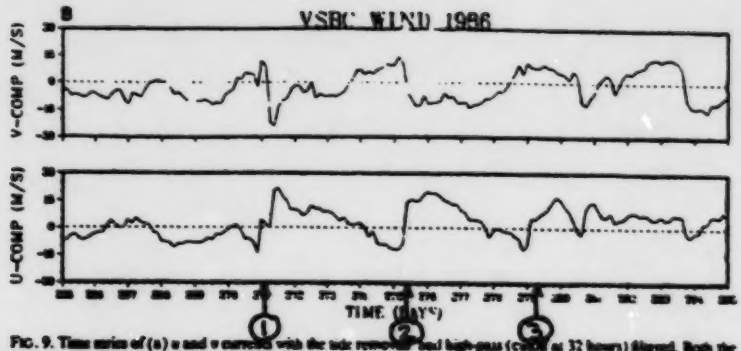


FIG. 9. Time series of (a) u and v currents with the tide removed and high-pass (cutoff at 32 hours) filtered. Both the upper layer (solid) and the lower layer response are shown. The wind velocity components as measured at a nearby oil rig (see Fig. 1) are shown in (b).

(b) RESPONSE:

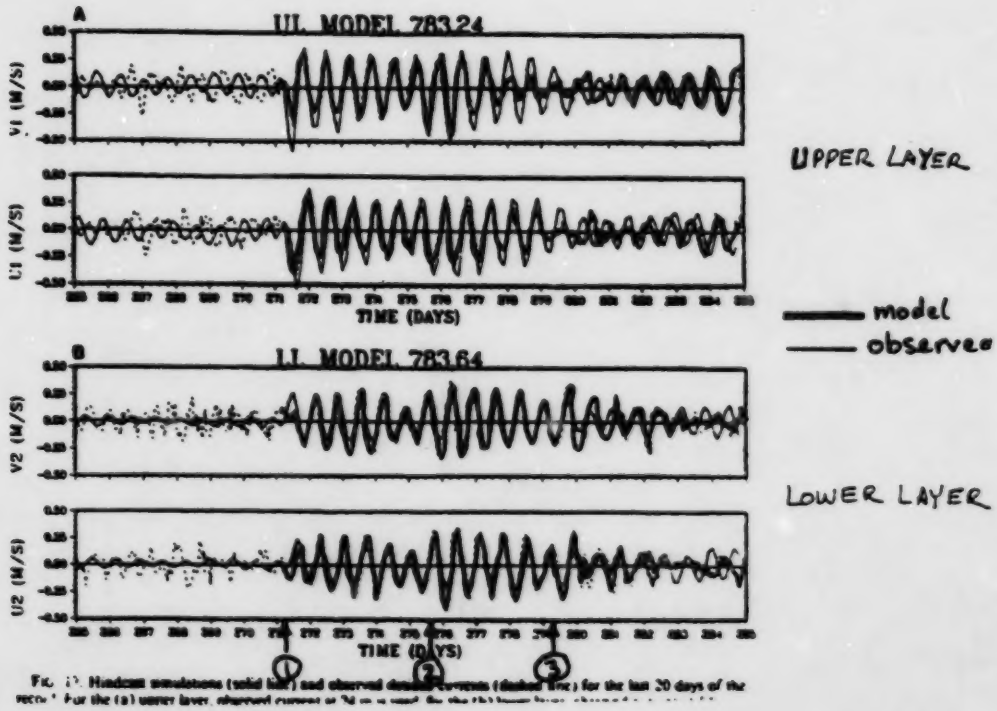


FIG. 10. Hindcast simulations (solid line) and observed [illegible] currents (dashed line) for the last 20 days of the record. For the (a) upper layer, observed current at [illegible] is used. [illegible]

Figure 8. (a) Time series of northward (V) and eastward (U) wind components measured by a nearby oil rig during the passage of the three storms, and
(b) Comparison of modelled and observed inertial currents in the upper and lower layers near Hibernia.

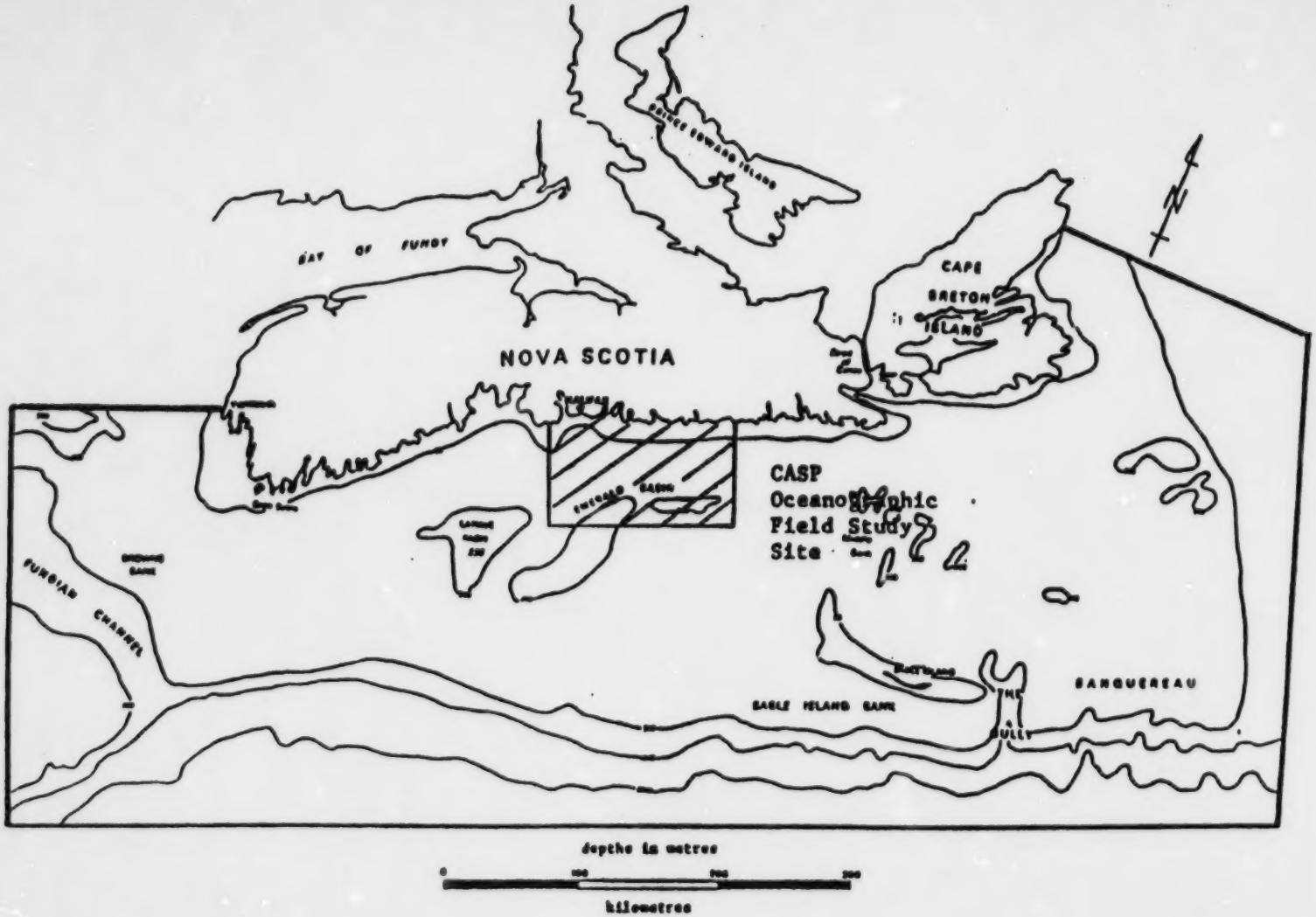


Figure 9. Scotian Shelf domain for the MEP OCS model that was tested against data from the Canadian Atlantic Storms Program (CASP).

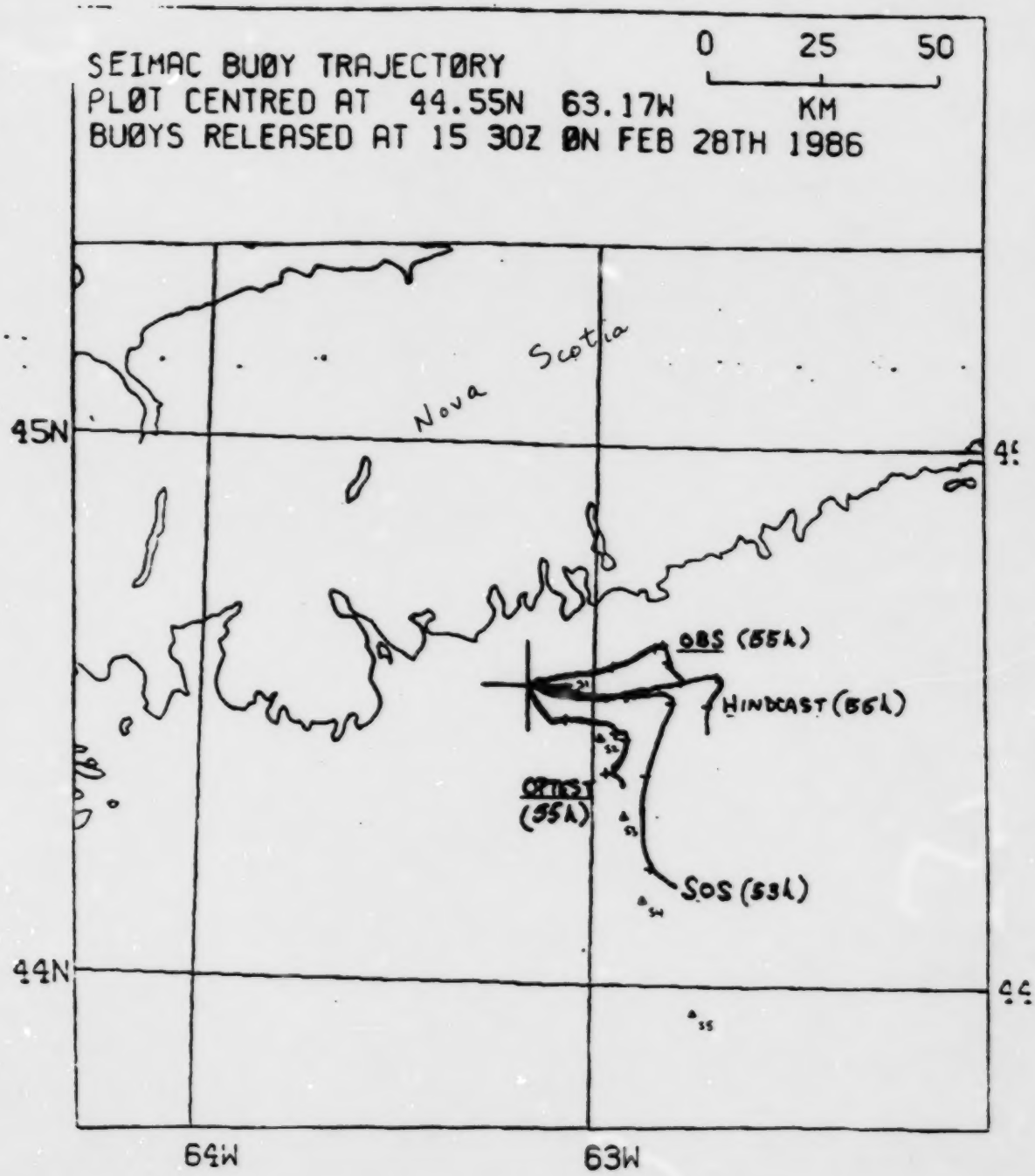
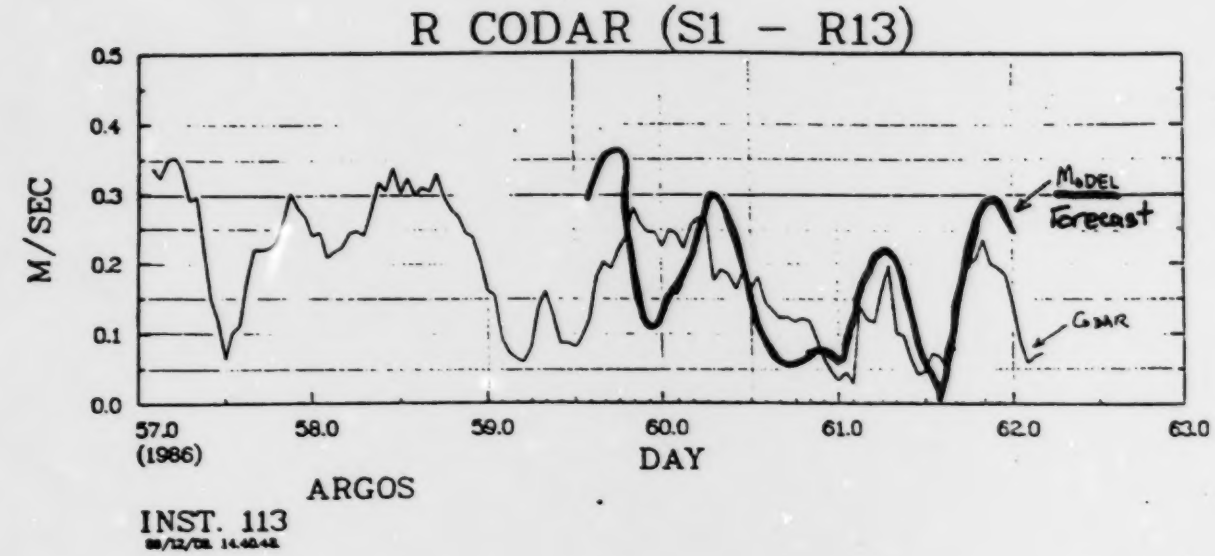


Figure 10. Comparison of observed trajectory (OBS) of Seimac drifter and simulations using MEP OCS model with forecast (OPTEST) and analyzed (HINDCAST) winds and the standard Coast Guard operational model (SOS). Solid triangles indicate CASP mooring sites.

(a) OPTEST



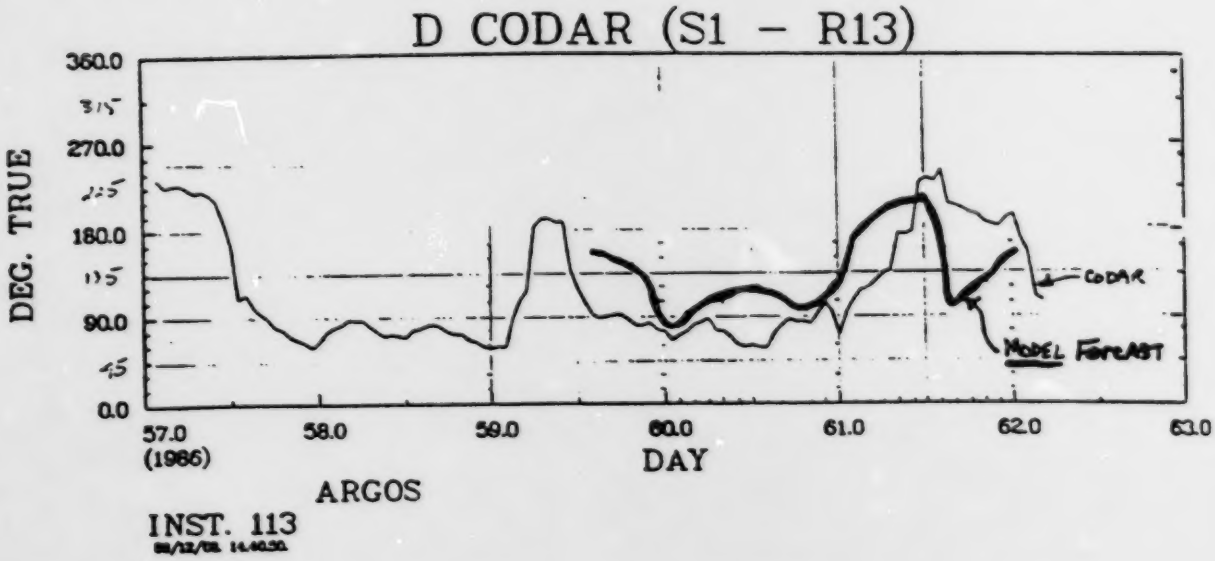
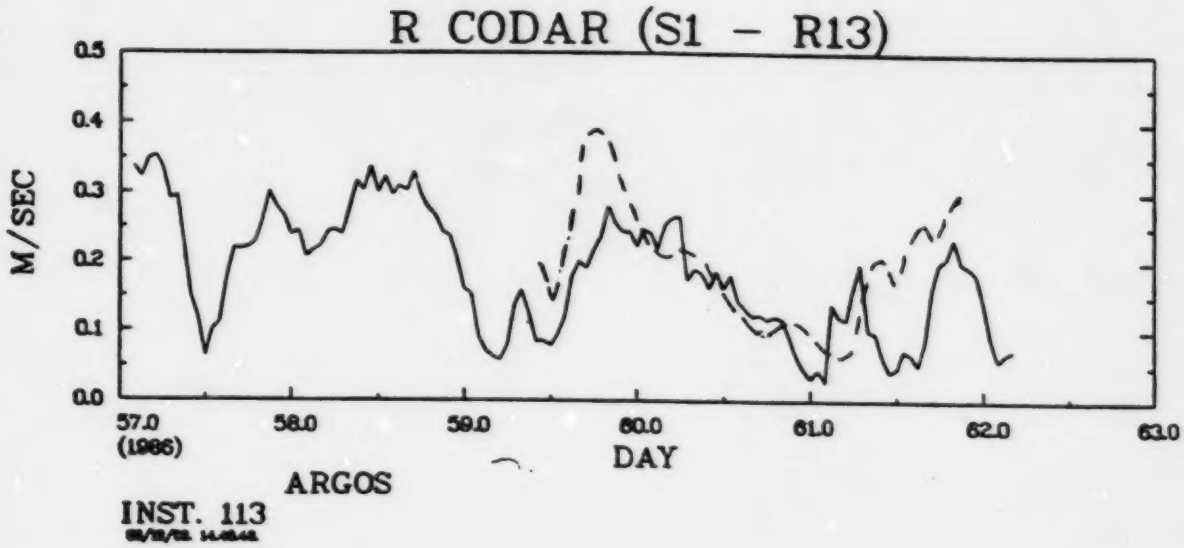


Figure 11a. Comparison of CODAR (thin, solid) surface current rate (R) and direction (D) against MEP OCS model with forecast winds (thick, solid).

(b) HINDCAST



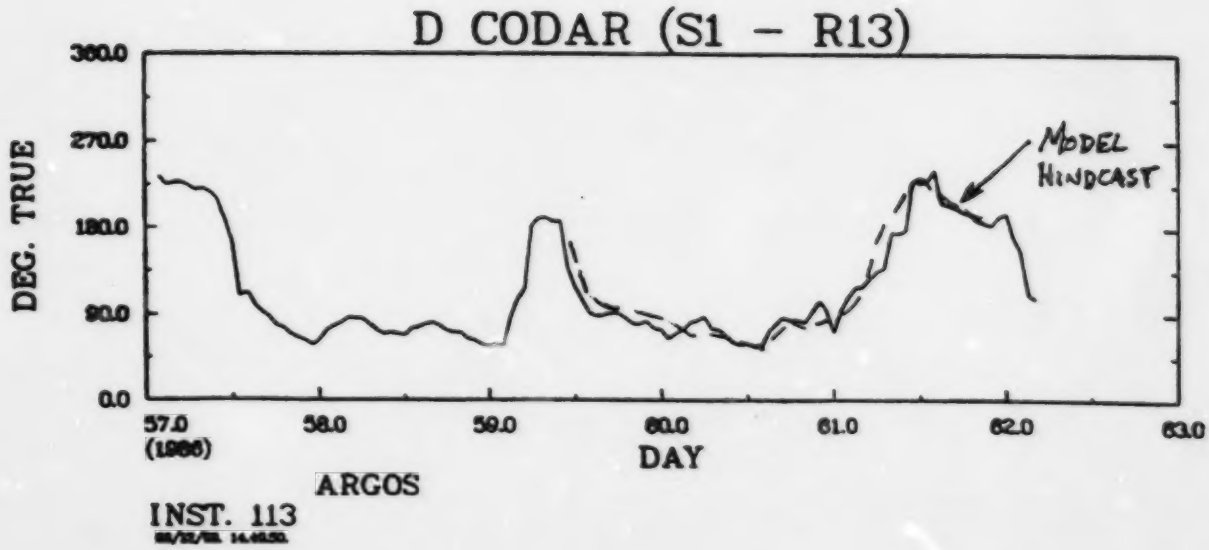


Figure 11b. Comparison of CODAR (solid) surface current rate (R) and direction (D) against MEP OCS model with hindcast winds (dashed).

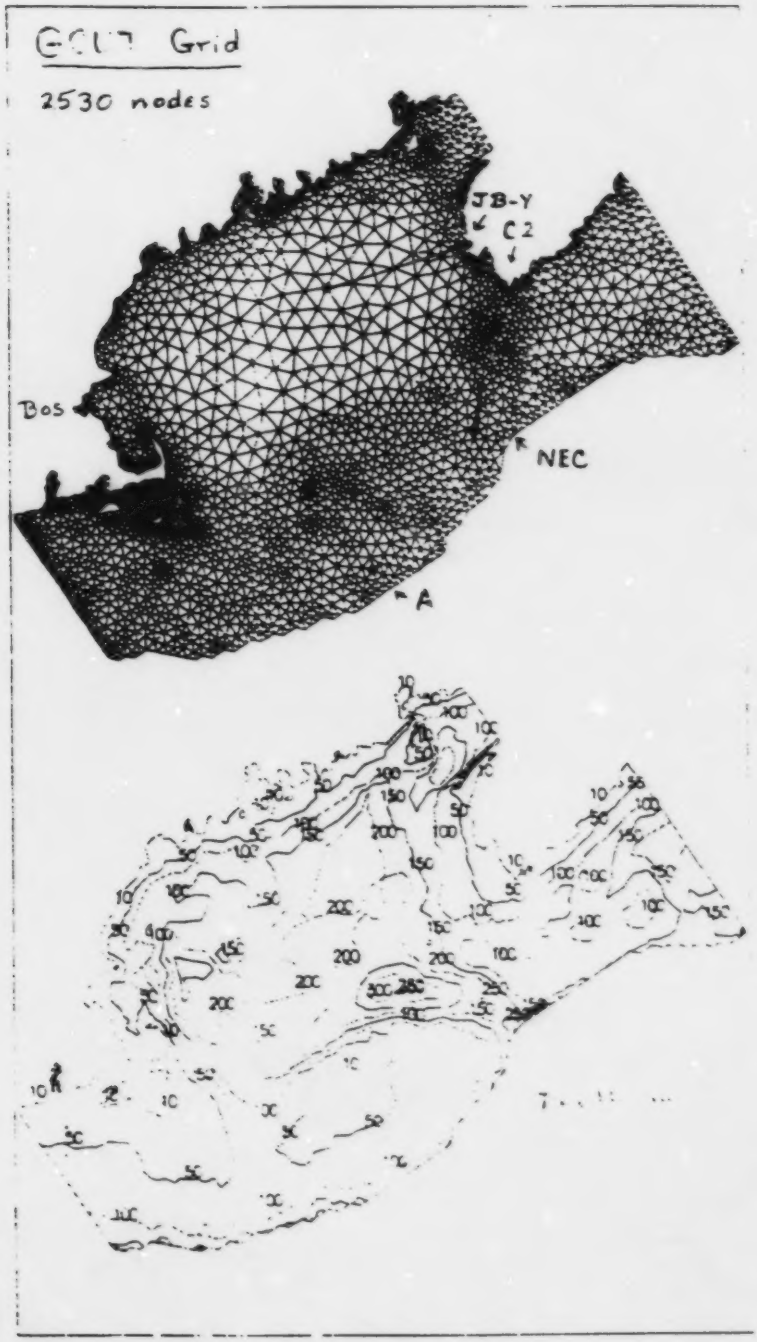


Figure 12. Finite element grid and bathymetry for the GLOBEC/PERD model for the seasonal circulation in the Gulf of Maine.

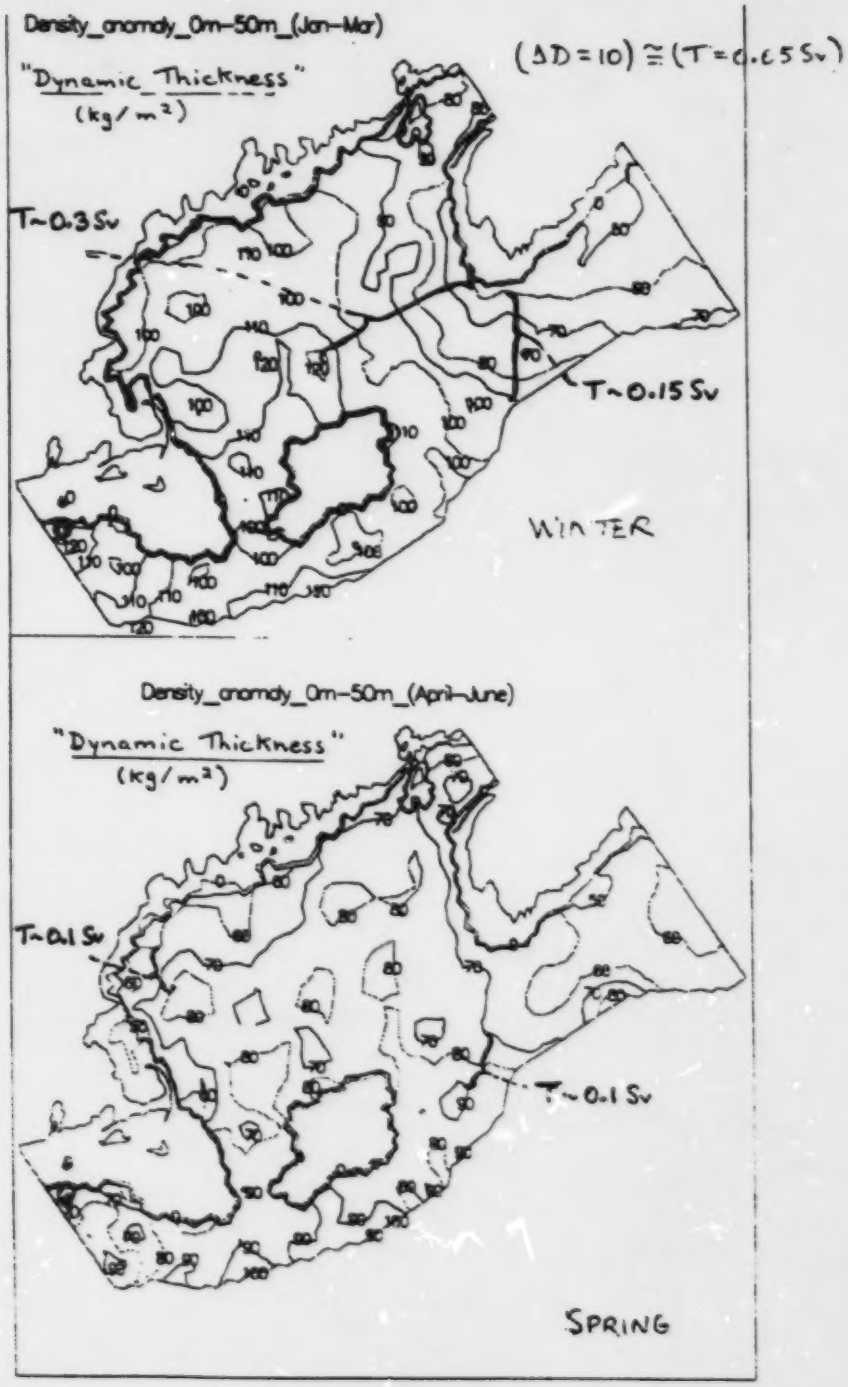


Figure 13. Dynamic thickness of the surface relative to 50 m, based on smoothed density anomalies from the AFAP climatological data base, for two seasons: winter (Jan-Mar) and spring (April-June).

SEMISPECTRAL PRIMITIVE EQUATION MODEL (Haidvogel et al, 1991)

Plate 2. (*Haidvogel et al.*) A sequence of horizontal maps of density and vertical velocity at 100 m depth for the central experiment: (a) day 140, (b) day 156, and (c) day 172. The colors have been chosen to reveal as much of the horizontal structure as possible. Any magnitude larger than 11 m d^{-1} is shown in dark blue or dark red. The individual minima and maxima of the vertical velocity are −19.4 m d^{-1} to 11.2 m d^{-1} (Plate 2a), −35.5 m d^{-1} to 17.7 m d^{-1} (Plate 2b), and −91.2 m d^{-1} to 90.9 m d^{-1} (Plate 2c).

Figure 14. A sequence of horizontal maps of density and vertical velocity at 100 m from the SPEM model for the Coastal Transition Zone in the California Current System (Haidvogel, et al, 1991). Contours represent density field and maximum shading indicates vertical velocities in excess of 11 m d^{-1}.

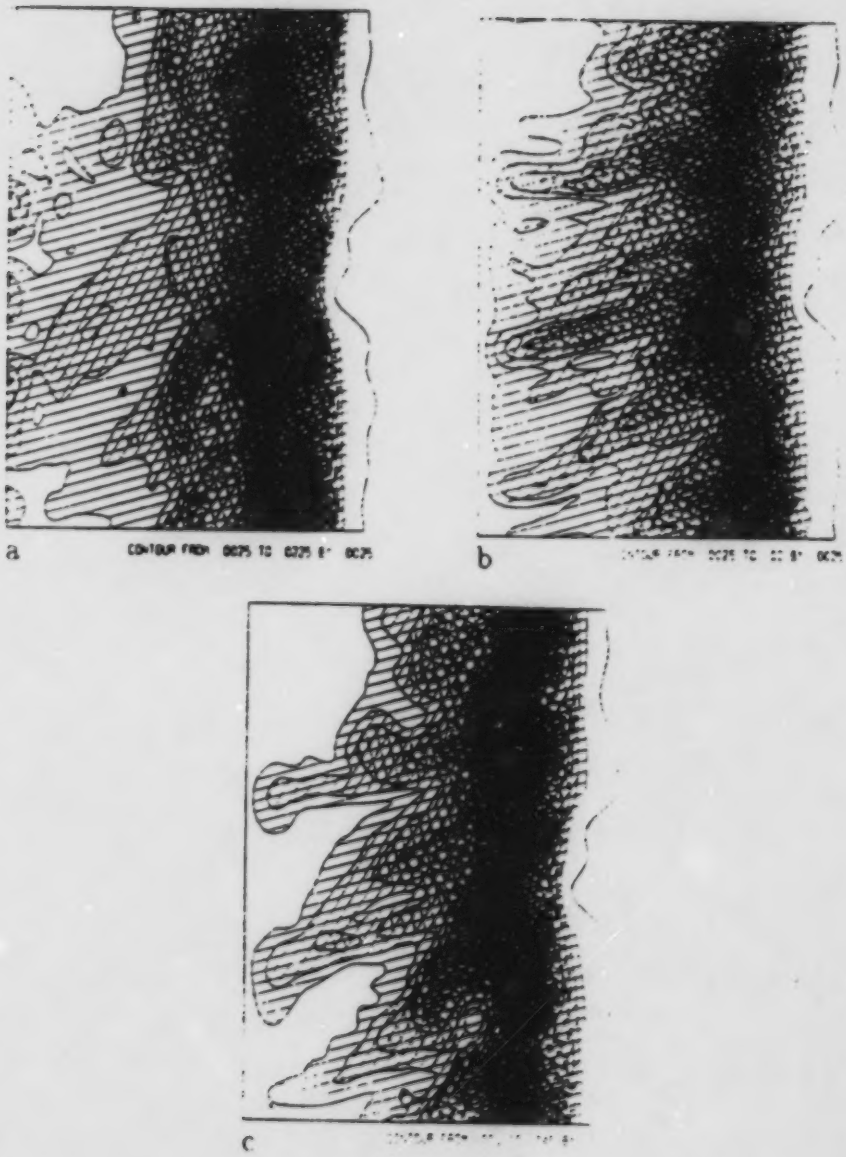


Figure 15. Current and density perturbation variances at 100 m from the SPEM model for the California Current System. (a) rms longshore velocity, (b) rms cross-shore velocity, (c) rms density perturbation.

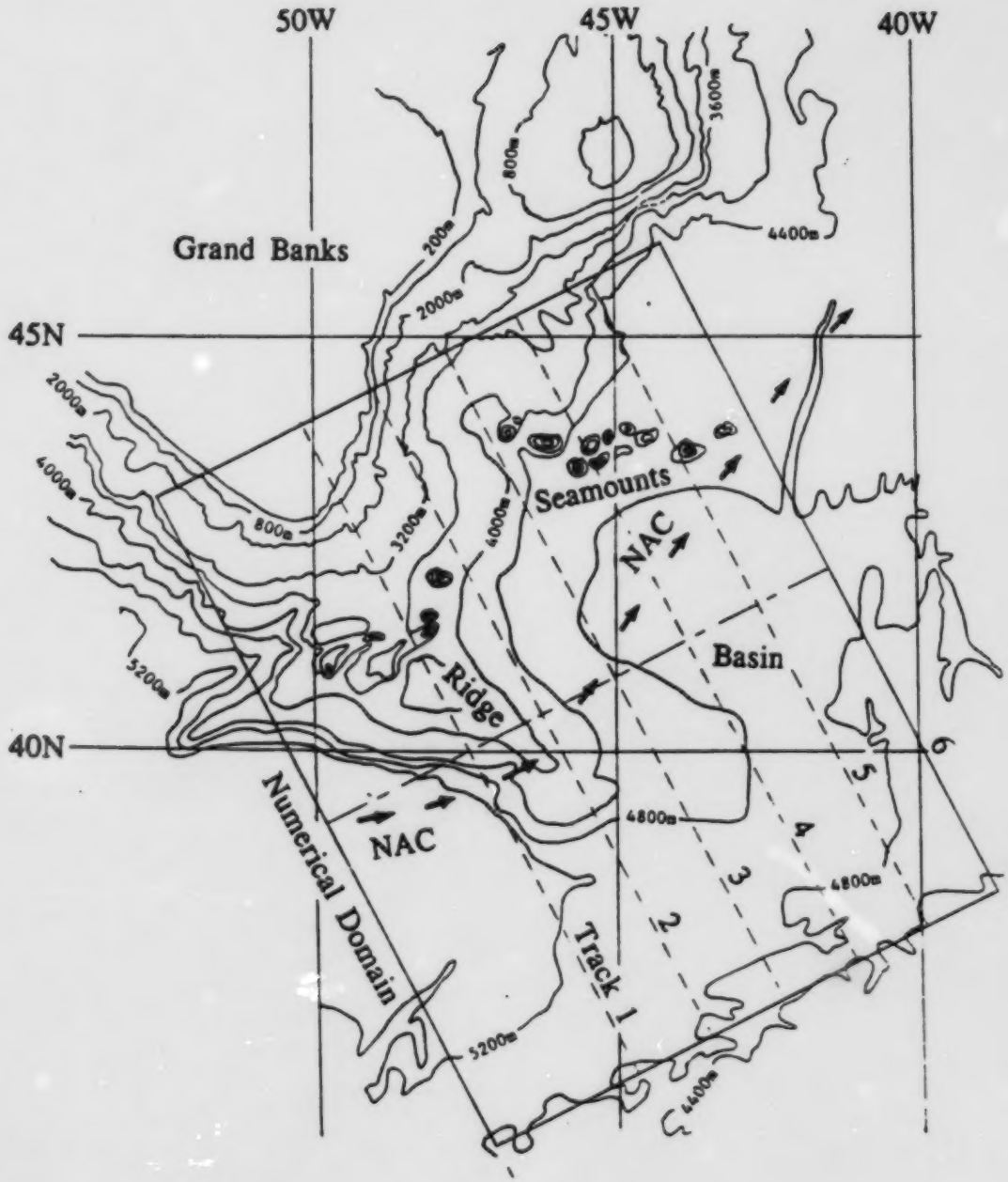


Figure 16. Model domain for Ikeda's quasigeostrophic (QG) model for assimilation of GEOSAT altimeter data. Successive tracks are separated by 100 km and 3 days. The GEOSAT repeat cycle is roughly 17 days.

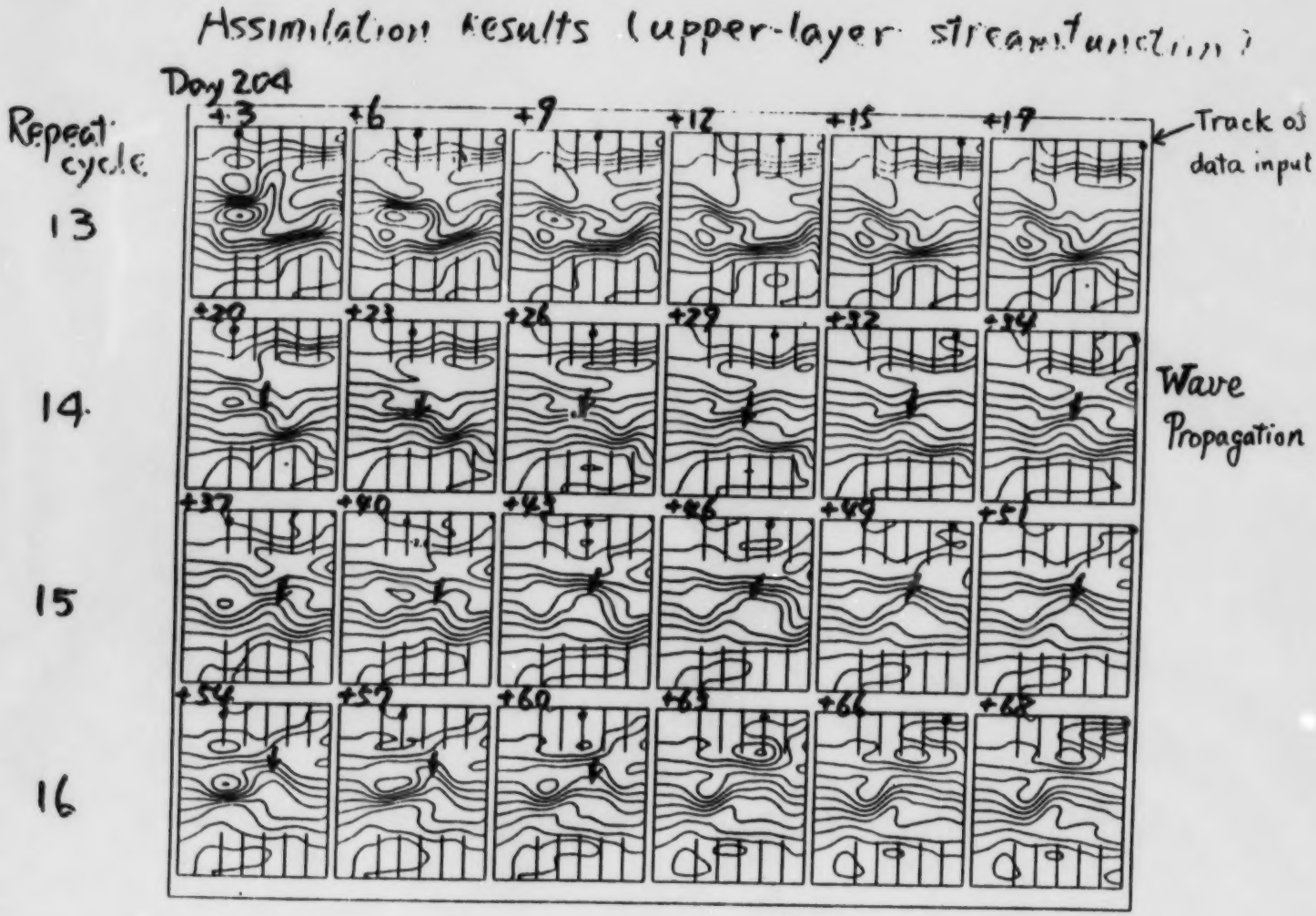


Figure 17. Upper layer streamfunction from the OG model for assimilating GEOSAT altimeter data. Solid dots identify successive tracks of input data and arrow indicates wavelike propagating feature in the results.

SUMMARY - CURRENT MODELLING SESSION

J. Elliott, Bedford Institute of Oceanography
B. Petrie, Bedford Institute of Oceanography

Before presenting the results of the 1992 deliberations about currents, the recommendations arising from the 1982 Mobil-BIO Grand Banks current workshop were revisited. The recommendations included:

1) Estimates for extreme currents were needed for design purposes. The methodologies to obtain them were discussed.
2) A hierarchy of models must be developed. They should include simple estimates, statistical and analytical models, and numerical models beginning with 1D, building towards a 3D.
3) Knowledge of the surface currents was required. The difficulties of modelling and measuring them were reviewed. New technology such as VMCMs and ADCPs was discussed.
4) The need for Lagrangian measurements using drifters, comparing successive satellite SST maps, ice and iceberg movement was stressed.
5) Iceberg trajectory modelling was reviewed and found wanting. "A model that hindcasts well is of limited value if inputs are difficult to obtain."
6) Another quote relevant for this meeting was - "There are reasons to doubt the value of oil spill trajectory models that have been used."
7) An industry/university/government steering group should be established to coordinate work and exchange information.

1992 WORKSHOP OBJECTIVES

NEEDS FOR OPERATIONAL MODELS

During the workshop presentations the needs of various groups were noted and include:

Industry	- as input for ice, iceberg and oil spill models; some requirement for design, scour and sediment transport.
Regulators	- for search and rescue; for a broad range to topics related to the EARP process; for operations
Model Operators	- besides developing models, this group, specifically the consulting firms, often makes research models operational; examples include iceberg and SAR models. At the workshop, considerable emphasis was placed on the user friendly requirement of current models. However, our working group concluded that the best way to convert research models to operationally friendly models was through consulting firms, i.e., the researcher should not be required to do it.
Researchers	- ice and oil spill applications; wave modelling, iceberg drift.

It was apparent through the working sessions that there is a great interest in having current models which can successfully nowcast and forecast near surface flows.

LINKAGES AMONG MODEL USERS

The working group thought that the relationship between researchers and developers was healthy. There have been examples of recent collaborations in the areas of ice and iceberg drift, tidal, wind-forced and mean current modelling. These collaborations will continue with programs such as CASP II.

The relationships between researchers and users with DFO are excellent with joint projects in the areas of fisheries, pollution and ocean chemistry. On the other hand, the interaction between researchers and users outside of DFO needs improvement. The needs of outside users for useful surface currents that was emphasized at this workshop were revealing. This is not a strong area of research in either our modelling or observation program. Though workshops and the PERD committees help, ongoing input is desired.

CONSTRAINTS TO IMPLEMENTATION OF OPERATIONAL MODELS

For many models the conversion to an operational mode could be straightforward - yet there is more emphasis on scientific publications which are not generally accessible to users or developers. The extra step of making an expert operational product is frequently neglected.

There is not the technical support to turn a research model into a more usable one.

It is difficult to obtain the necessary input data (e.g. winds, altimetry) on a regular basis.

PRIORITY AREAS FOR RESEARCH MODELLING

1) Choice of model should be based on what is appropriate, useful and practical. If a 1D model works for an application and there is good reason why it should, use it. We do not buy the argument put forward during the meeting that current modelling should go to 3D now. However, development towards 3D models should continue.

2) Data assimilation appears to be a promising technique to improve model performance and to lead to additional development. More emphasis should be given to it.

3) Greater attention must be given to near surface currents, in particular, with regard to ice and oil spill modelling.

4) Attention and improvement to access of data that serve as inputs to current models, e.g., winds and satellite data.

5) The establishment of a current modelling steering group providing an ongoing exchange among all players will greatly benefit model development by providing focus to important problems.

Subsequent to the meeting, a number of participants indicated that they would like to see more effort towards having the results of some of the DFO models available at least to the expert user. This suggestion has merit and will be considered.

OIL SPILL TRAJECTORY MODELLING

Chairman: Rainer Engelhardt, Marine Spill Response Corporation

Rapporteur: Jim Osborne, Environment Canada
Rapporteur: Charles Giammona, Marine Spill Response Corporation

SUMMARY
RESEARCH, DEVELOPMENT AND OPERATIONAL USE OF OIL SPILL TRAJECTORY MODELS

A review was made of oil spill trajectory models, current models, and wave models to provide a synopsis of present capabilities in Canada. The review focused on operational needs, the present status of operationally-oriented models, ongoing and planned research and linkages between the operational, development and research communities.

The review provides general information on model components and expected performance; it was not intended to provide detailed technical specification concerning model parameterization or physics. The important components of the models were reviewed for the purpose of providing an overall indication of capabilities, rather than to provide a basis for selecting operational models for given applications.

The purpose of the review was to serve as a discussion paper. It is anticipated that it will be used by interested parties to develop their own recommendations pertaining to future research and model development.

Reference: Godon, A., D. McGillivray and D. Dickins. 1991. Status: Research, Development and Operational Use of Ocean Models. Prepared for the Panel on Energy Research and Development by D.F. Dickins Associates Ltd. and the MEP Company Ltd.

BACKGROUND

The Panel on Energy Research and Development (PERD) undertook a study to evaluate the direction of research efforts required to provide effective oil spill trajectory, current and wave models for operational use. The following sections summarize the results of the current model review. Further detail is available in Godon *et al*, (1991) which is included as an Annex to these proceedings.

While the review was intended to be comprehensive, it was acknowledged at the outset that time and budget considerations would potentially constrain this objective. However, it was felt that the results would provide a useful foundation upon which to build during the Workshop. At that time, comments and additions were solicited from Workshop participants. These have been compiled and follow the summary.

The review included an examination of communications linkages between researchers, developers, operators and users of models. The objective of this aspect of the review was to identify deficiencies in existing linkages in order to improve future mechanisms whereby research efforts can lead to more effective operational products.

For the purposes of the review, an "operational model" was defined as a numerical prediction system which processes forecast or observed inputs to compute output forecast products such as oil spill trajectories. Models which were considered potentially operational were defined as "operationally-oriented". To be classified in this manner, a model would not presently be in regular use, but would have been designed and tested to run in a realistic operational setting.

OIL SPILL TRAJECTORY MODELS

Operational oil spill trajectory models are used in Canada by spill response personnel in the petroleum industry, Environment Canada, and Coast Guard. Within the petroleum industry

individual oil companies and response organizations such as the Beaufort Sea Coop use spill trajectory models for contingency planning, emergency response, and training exercises. Within Environment Canada, Conservation and Protection makes similar use of spill trajectory models but with greater emphasis on emergency response. The Canadian Coast Guard uses trajectory models for strategic contingency planning and preparedness.

Modelling requirements expressed by industry and government users include the following:

- capability for real-time input of environmental data
- flexibility (ability to upgrade sub-model components; accommodation of variable input data formats)
- user-friendly interface
- improved fate and behaviour models

Ten oil spill trajectory models were reviewed including three American models. The models were found to use the same basic principles to predict advection and spreading. As well, the models tend to use some formulation of Mackay's work to predict evaporation, dispersion, and emulsification. The models differ in their treatment of input data, grid sizing, transportability to other regions, and the capability to predict evaporation, dispersion, emulsification, oil-in-ice spreading, and shoreline impact.

OIL SPILL TRAJECTORY MODEL CHARACTERISTICS

Models have been developed for a variety of purposes: emergency response, contingency planning, training, and damage assessment. As a result, different types of models and different modes of operation have evolved:

Forecast mode	uses forecast environmental data to predict oil trajectory and fate in real-time;
Statistical mode	uses statistical or randomly selected environmental data to run many trajectory scenarios for a given point or area;
Receptor analysis	used to delineate spatial and temporal impacts of a given spill; and
Hindcast mode	uses historical input data to compare predicted spill behaviour with observed behaviour.

However in general, oil spill trajectory models have two components, the first incorporating algorithms to simulate the trajectory of the oil and the second incorporating fate and behaviour algorithms to describe the spreading and weathering of the oil.

As output, most models produce screen displays and hardcopy maps showing the trajectory and extent of the oil at user-defined time intervals. Depending on the fate algorithms used, tables showing the oil mass balance at different stages of weathering or impact with a shoreline can also be produced.

OIL SPILL TRAJECTORY MODELS REVIEWED

Table 1 summarizes the trajectory models intended for operational use in Canada. Also included are several models in use in the United States.

Table 1
Summary of Operationally-Oriented Oil Spill Trajectory Models

Model (Developer)	Primary Purpose (User)	Input Data	Input Format of Winds/Currents	Spreading	Evaporation Dispersion Emulsification	Computer System	Output (Resolution)
Beaufort Sea Co-op (ASA/Gulf)	emergency response, planning (Beaufort Sea Co-op)	wind, ice cover, current model (tidal & residual) oil properties, spill volume and type, location	uniform, time varying wind; 3-D hydrodynamic current model for area (spatial and time varying)	Fay's 3 regime	yes-Mackay yes-Mackay Yes-Mackay	IBM 386	trajectory, extent, shoreline impact, mass balance (~300 m)
MIRG SL Ross (SL Ross ERL)	emergency response, dispersant use decisions (MIRG member companies)	winds, residual, currents, oil properties, spill location, shorelines	uniform, time varying wind; gridded currents	modified Fay with Mackay thick/thin	yes-Mackay yes-Audunson yes-Mackay	IBM PC	trajectory, extent, mass balance, ecological impact, (user-defined)
OILBRICE (Fleet Tech. AES, Crescent Consulting, Greenhorne & O'Mara)	emergency response, planning, (MMS, AES)	winds, residual and tidal currents, air temperature, ice cover, oil properties	dependent on trajectory model	empirical (in and out of ice)	no no no	IBM PC	trajectory, extent, thickness, mass balance in ice (1 km resolution)
Oil Spill Model Shell (ASA)	emergency response, planning, training (Esso Canada, CPA, Environment Canada)	wind spd/direct, residual currents, shorelines	uniform, time varying wind; gridded currents	Fay's 3 regime	yes-Mackay yes-Mackay yes-Mackay	IBM PC	trajectory, mass balance (default 10 km resolution)
OSP Model (ENSR)	emergency response, planning, permitting (Alaska Clean Seas)	winds, residual currents, waves, shoreline, ice cover	uniform, time varying winds; gridded currents	Fay's 3 regime	yes-Mackay yes-Mackay yes-Mackay	Compaq 286	trajectory, mass balance (lat/long grid-variable)
OSSM (NOAA)	emergency response, planning (NOAA)	winds, residual and tidal currents, shoreline, oil properties, location	gridded, time varying winds and currents or current model	turbulent diffusion	yes no no	IBM PC or Macintosh II series	trajectory, mass balance, shoreline impact (variable res.)
SCOOP (Esso & Scicon)	emergency response, planning (Esso)	wind, residual and tidal currents, shoreline, oil properties	interpolated time varying wind data; currents from atlas (gridded, time varying)	no model	yes-Mackay yes-Mackay no	SUN workstation	trajectory, thickness (hourly, variable res.)

Table 1
Summary of Operationally-Oriented Oil Spill Trajectory Models (continued)

Model (Developer)	Primary Purpose (User)	Input Data	Input Format of Winds/Currents	Spreading	Evaporation Dispersion Emulsification	Computer System	Output (Resolution)
SLICK II (AES)	emergency response, planning (AES)	winds, residual currents, tidal currents, oil surface tension, spill location, spreading coefficient	gridded, time varying winds and currents; variable resolution grid	Fay's 3 regime with turbulent dispersion	yes-Mackay in advection yes-Mackay	Mainframe	trajectory plot thickness, extent, shoreline impact, mass balance (variable resolution)
SLICK PC (AES)	emergency response (AES)	winds, residual currents, tidal current, oil surface tension, spill location	uniform, time varying wind; uniform residual current; uniform time varying tidal current	Fay's 3 regime	no models	IBM PC or HP 9000	trajectory plot (1 nmile, 1 hourly time step)
SPILLSIM (Seaconsult)	emergency response, planning	winds, current model (residual, and tidal), oil properties, waves	gridded, time varying wind and currents; currents from model, current atlas or HF radar	Mackay	yes-Mackay yes-Buist yes-Mackay	IBM 486	trajectory, extent, thickness, mass balance (15 km square)

OIL SPILL TRAJECTORY MODELLING AND RELATED RESEARCH

Considerable research is being conducted in the area of oil fate and behaviour and attention is also being directed to the environmental data inputs to models. A recent trajectory modelling workshop held by Environment Canada pointed to the requirement for additional field measurements to support verification of oil in ice models and for general improvements in ocean current input.

Work with HF (High Frequency) radar systems to map surface currents is of particular interest for improved ocean current input. Seaconsult Marine Research Ltd. is marketing a CODAR system called SeaSonde which will be tested in the coming year. The system will have the ability to provide real-time maps of sea surface currents for input to trajectory models. A similar system is being developed at the Centre for Cold Ocean Resources Engineering (St. John's, Newfoundland). Research in progress or conducted in the past year is summarized in Table 2.

OPERATIONAL/RESEARCH LINKAGES

Linkages between operations and research groups were studied with an interest in identifying areas where the operational utility of models could be enhanced through improved communications, or better information transfer. Through the review, it was found that while linkages could be

identified between researchers, model developers, model operators and users of model output, the strength of these linkages varied.

Table 2
Oil Spill Trajectory Models: Research Efforts

Organization	Research Areas
Atmospheric Environment Service S. Venkatesh	shoreline impact aspects of models, oil in ice, and improving user interface.
Environment Canada M. Fingas	long-term evaporation, photo-oxidization, emulsification, and solubilization.
Esso Resources Canada Limited A. Holoboff	improving evaporation algorithm, developing beaching algorithm, improving graphical display and user interface.
S.L. Ross Environmental Research Ltd.	improving fate and behaviour algorithms, and developing different spill scenario models.
Seaconsult Marine Research Ltd.	improving hydrodynamic models, interfacing to real-time measurement of currents from HF radar, interfacing with remote sensing data.
University of Toronto D. MacKay	improving algorithms for weathering and dispersion.
Warren Springs Laboratory T. Lunel	droplet modelling of oil slicks.

In the case of oil spill trajectory modelling, the linkage between researchers and developers was based largely on published information. Reliance on this remote linkage was seen as an impediment to model development. This obstacle was sometimes accentuated by the fact that developers tended to have expertise either in oil spill technology or in oceanography but not necessarily both critical components to oil spill trajectory models. As a result, state of the art research in one area or the other might not be readily incorporated into model developments as readily as possible.

The user's relationship to the oil spill research and development communities was seen as being irregular. Within Environment Canada, model users and researchers communicate through the Environmental Sciences Division, interacting on operational concerns and research proposals. PERD provides an important mechanism by which the user community can have input into directing research efforts. Between the model user and model developers, the importance of user's taking a proactive approach was stressed, whether this was in terms of direct contracting to have a model developed or in becoming familiar with an off-the-shelf model before acquisition. In both cases, informed interaction between user and developer was seen as valuable for subsequent model refinement.

WORKSHOP RESPONSE TO THE OCEAN MODEL REVIEW
OIL SPILL TRAJECTORY MODELLING COMPONENT

A review of operational and research ocean models was prepared for PERD (Status: Research, Development and Operational Use of Ocean Models by D.F. Dickins and the MEP Company) for distribution and comment at this Workshop. While the full review is attached as an appendix to these proceedings, comments from Workshop participants pertaining to the review are noted here.

COMMENTS CONCERNING THE REVIEW DOCUMENT

p. B-5 — It was noted that HF radar systems are limited in range and thus are only suited to coastal areas and the vicinity around fixed platforms.

The cost of HF radar system installations was also raised as a potential constraint to their effective implementation.

p. B-19 — Even in areas where HF radar systems installations exist, there may be a need for current information through the upper ocean layer, if oil is distributed below the surface. This information could not be derived from HF radar alone and would benefit from a dynamics-based current model.

RECOMMENDATIONS FROM A NATIONAL WORKSHOP ON OFFSHORE OIL SPILL MOVEMENT AND RISK ASSESSMENT

Robert P. LaBelle
Minerals Management Service
U.S. Department of the Interior
Herndon, VA

The Offshore Oil Spill Movement and Risk Assessment Workshop was held November 7-9, 1990, in La Jolla, California, to identify oceanographic observations and models that would improve the information used in analyzing risks from offshore oil and gas development. The goal of the workshop was to recommend methods of assessing or estimating how oil spills move in the ocean. Attendees included leading researchers from academia, government and private industry. Participants were asked to recommend methods that could use observations and models that are presently available, as well as to recommend more long term observation and research that would be needed to support an "optimum method".

A working group on oil-spill transport identified three categories of oceanographic observations and methods that would lead to a credible means of oil-spill trajectory analysis:

(1) a major study of upper ocean Lagrangian transport, leading to an observational base that would generate a statistical model, as well as provide direct observations of actual particle trajectories in the ocean;

(2) a long-term scientific approach toward the development of rigorously evaluated, dynamically based upper ocean models, which would be used to generate "drifter tracks" from potential spill locations and to greatly extend sparse databases; and

(3) quantitative, process-oriented research to understand horizontal dispersion of particles and oil in the uppermost water column, convergence, and flow at the very surface of the ocean.

The working group on oil-spill fates concluded that the critical limiting factor in spill risk assessment is the fundamental knowledge of oil-spill dispersion and spreading. Inherent in this uncertainty is the inability to predict or measure oil-slick thickness, emulsification formation, and oil-spill shoreline interaction. The group made the following recommendations:

(1) link oil spill fate and trajectory models when possible, assimilating new process knowledge as it becomes available;

(2) compare and document alternative algorithms for spreading and fates, including parameter and validation studies;

(3) use long-term field studies to investigate vertical dispersion, horizontal spreading, oil droplet size and distribution, and effects of Langmuir circulations and fronts; and

(4) study fundamentals of oil spill/shoreline interactions.

REFERENCES

Minerals Management Service, Offshore Oil Spill Movement and Risk Assessment Workshop, Interim Report, OCS Study MMS 91-0007, February 1991.

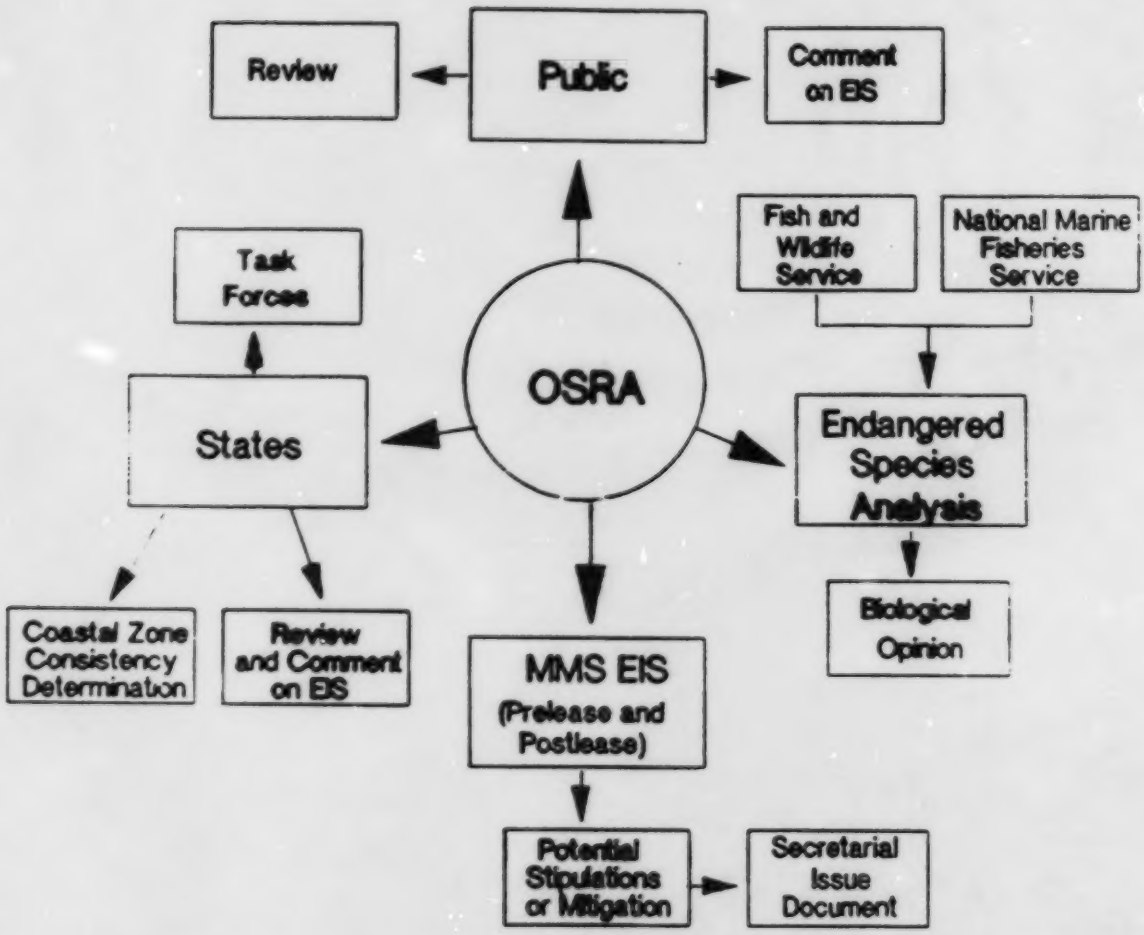
WHY IS OIL-SPILL RISK ASSESSMENT NEEDED?

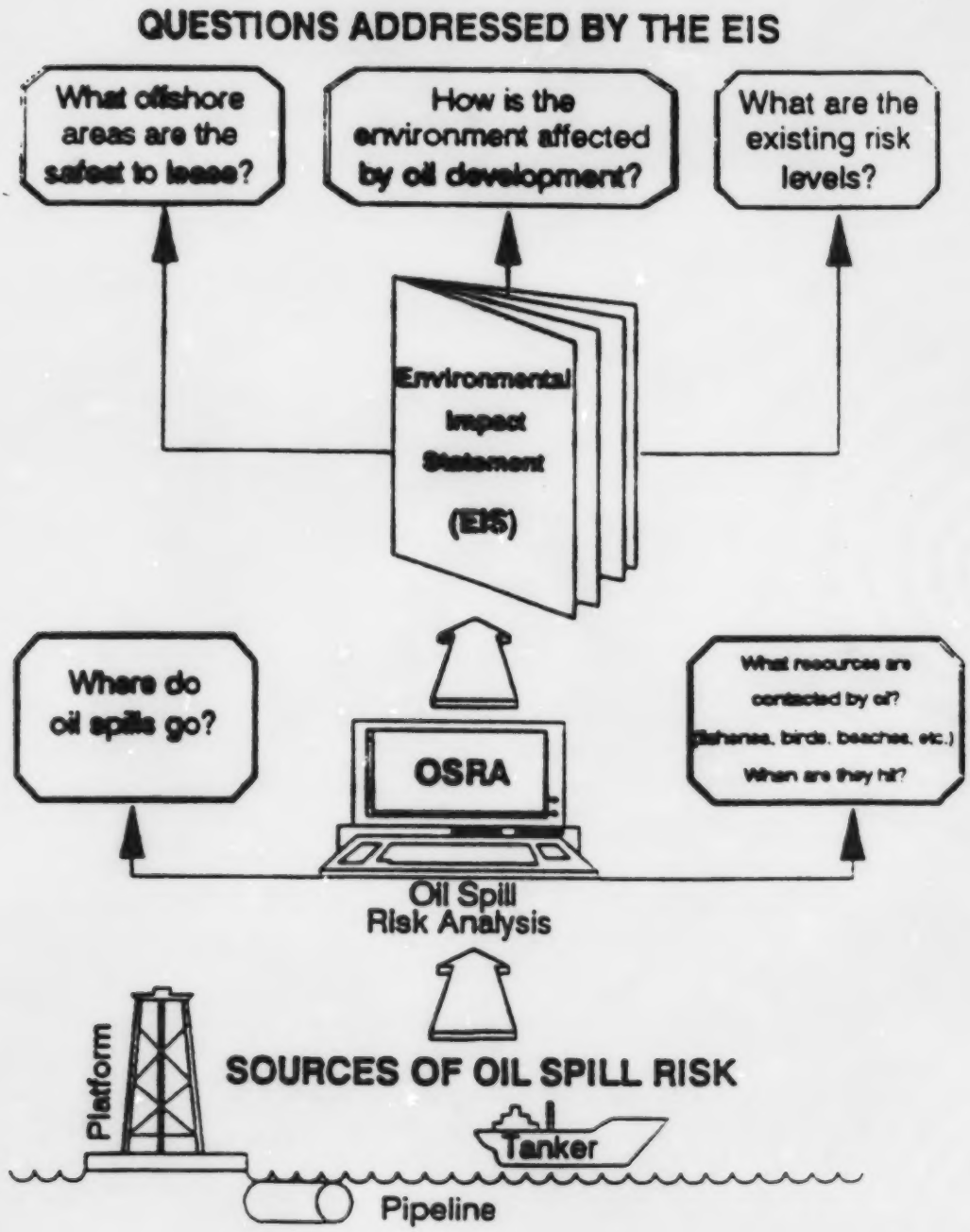
- OIL SPILLS -
"THE" MAJOR CONCERN OF PUBLIC, STATES

KEY QUESTIONS:
- **WHERE WILL SPILLS GO?**
- **WHAT RESOURCES ARE AT RISK?**
- **HOW CAN WE PROTECT THESE RESOURCES?**

NEED FOR PLANNING:
- **OIL SPILL CONTINGENCY PLANS**
  - **PREVENTION**
  - **CONTAINMENT**
  - **CLEANUP**
- **SELECTING OFFSHORE LEASE AREAS**

Figure 1.
Users of Oil Spill Risk Analysis (OSRA) results.




QUESTIONS ADDRESSED BY THE EIS
What offshore areas are the safest to lease?
How is the environment affected by oil development?
What are the existing risk levels?
Environmental Impact Statement (EIS)
Where do oil spills go?
OSRA
What resources are contacted by oil? (fisheries, birds, beaches, etc.) When are they hit?
Oil Spill Risk Analysis
Platform
SOURCES OF OIL SPILL RISK
Tanker
Pipeline

ADEQUACY OF MODELING

Some Major Findings of 1990 Oil Spill Risk Assessment Workshop:

Numerical models are a valuable tool, but have fallen short of their potential

Insufficient use of Lagrangian observational approaches to risk assessment

Lack of Knowledge in Following Areas:

Basic physics of the surface layer (upper 2 meters)

Oil-Spill dispersion and spreading (emulsification)

Oil spill-shoreline interactions

EXISTING APPROACHES TO OIL SPILL RISK EVALUATION USED BY MMS

BENEFITS OF FORMAL RISK ASSESSMENT

* CALCULATIONS BROUGHT UNDER SCIENTIFIC SCRUTINY

* INFORMS PUBLIC OF THE BASIS FOR DECISIONS, UNCERTAINTIES AND ALL

* RISK ANALYSIS PROCESS HIGHLIGHTS THE UNCERTAINTIES OF RISK ESTIMATES, WHICH IN TURN SUGGESTS A RESEARCH AGENDA TO RESOLVE THESE UNCERTAINTIES

NOTE:

* OVERALL GOAL IS NOT CERTAINTY, BUT TO IMPROVE DECISIONMAKING.

* UNCERTAINTY DOES NOT IMPLY LACK OF KNOWLEDGE.

MMS OIL-SPILL MODELING

PRESENT STATUS:

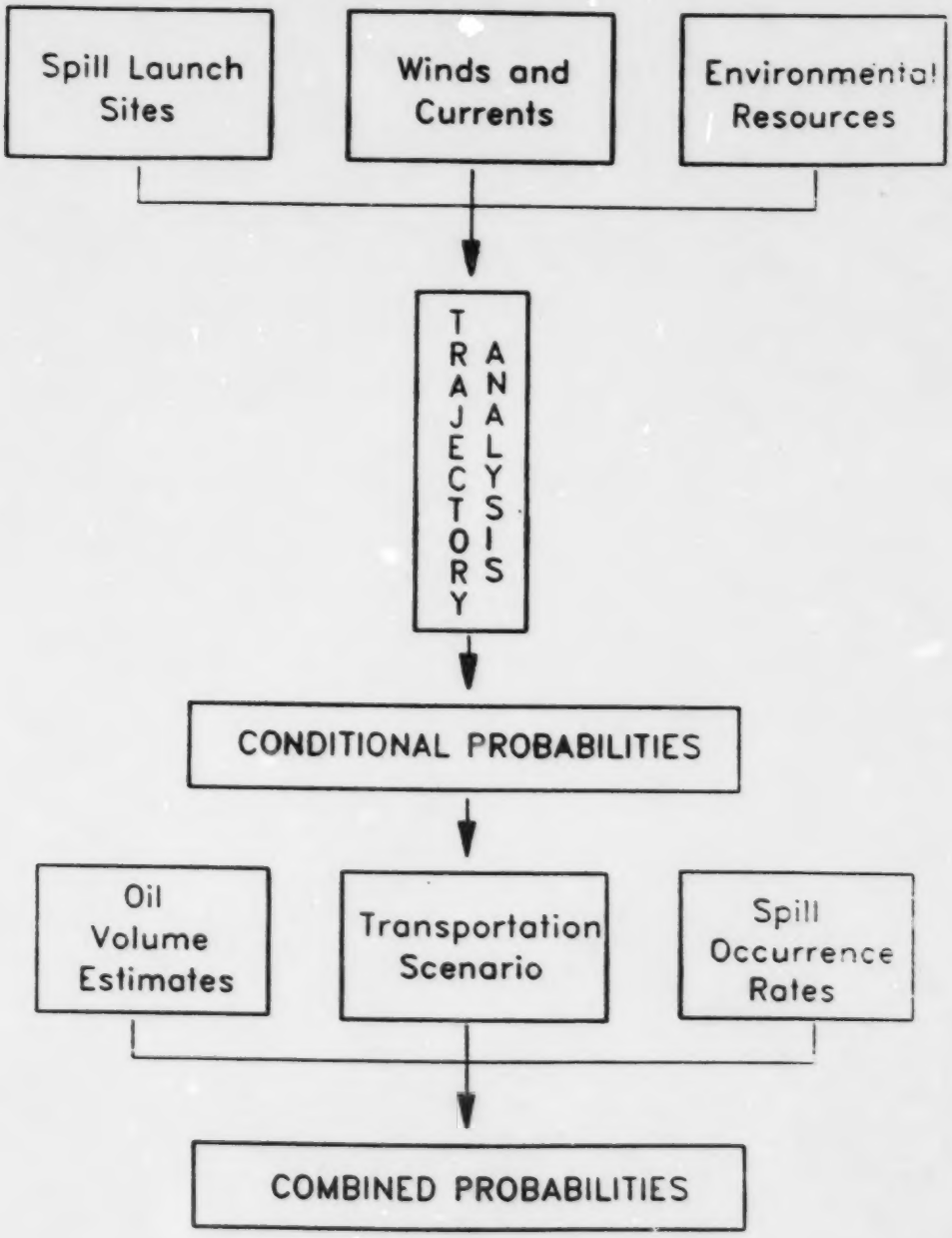
STRONG INTER-AGENCY TIES

- U.S. NAVY
- NOAA
- USCG
- MSRC

ACADEMIC PARTICIPATION

- MODELING REVIEW BOARD
- SCIENTIFIC REVIEW BOARDS
- SCIENTIFIC ADVISORY COMMITTEE

OSRA PROCESS



OIL-SPILL MOVEMENT ON THE OCEAN

DRIVEN BY:

- WINDS
- OCEAN CURRENTS
- SMALLER SCALE PROCESSES
  - TIDES, WAVES
  - EDDIES
  - STORM FRONTS
  - ICE

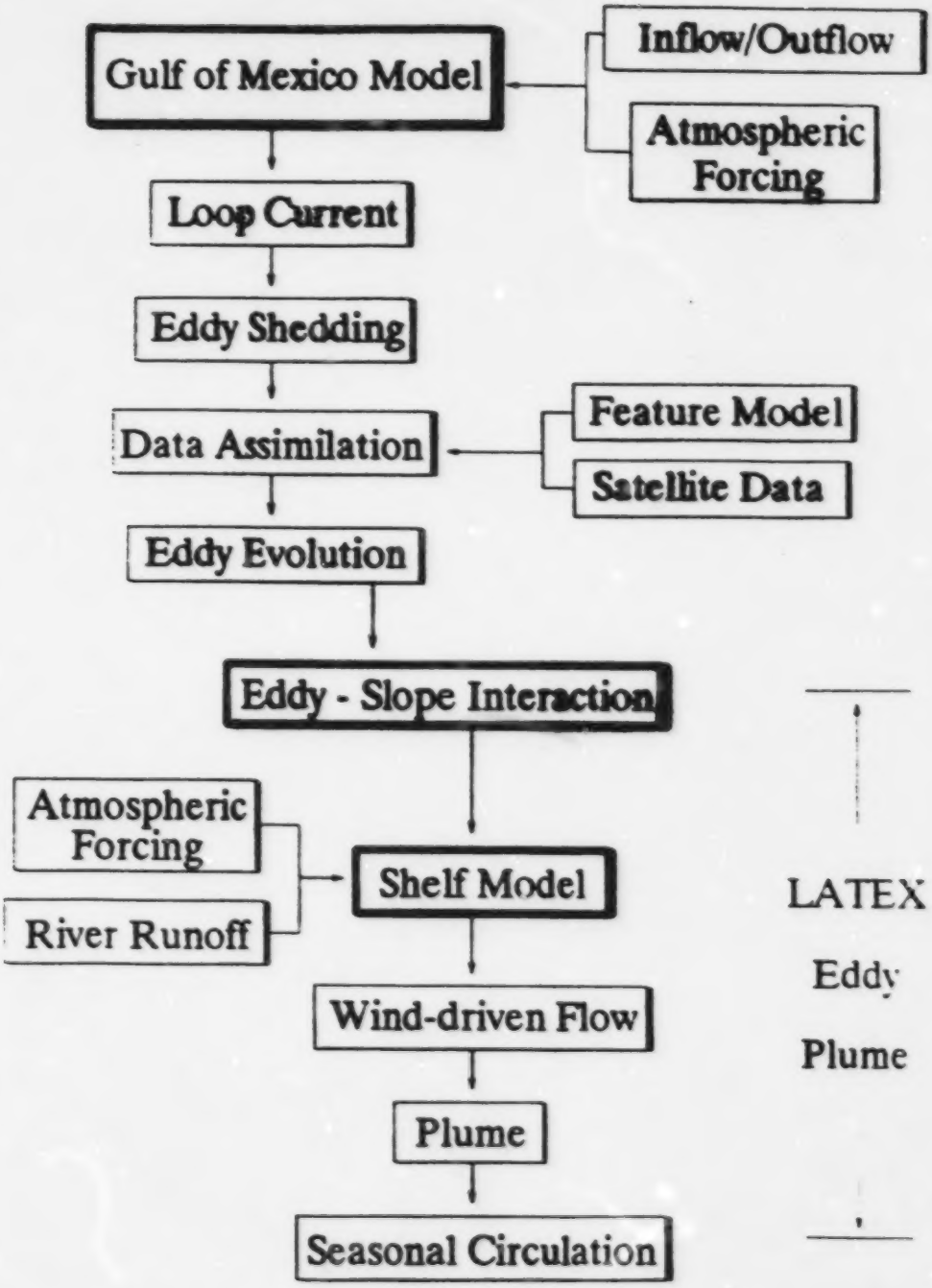
ESTIMATED BY:

- OBSERVATIONS
- MODELS
- COMBINATIONS OF THE TWO

A Preview of the MMS Ocean Modeling in the Gulf of Mexico with Emphasis on the LATEX Area

Outline of Major Tasks

- Process Studies
- Process-Oriented Calculations
- Deterministic Modeling
- Skill Assessment
- Statistical Modeling
- LATEX-Modeling Interaction


Gulf of Mexico Model
Inflow/Outflow
Atmospheric Forcing
Loop Current
Eddy Shedding
Data Assimilation
Feature Model
Satellite Data
Eddy Evolution
Eddy - Slope Interaction
Atmospheric Forcing
River Runoff
Shelf Model
Wind-driven Flow
Plume
Seasonal Circulation
LATEX
Eddy
Plume

1991 OIL SPILL RISK ASSESSMENT WORKSHOP

INSTITUTIONS REPRESENTED

Woods Hole Oceanographic Institute

NOAA HAZMAT

University of Alaska

Oregon State University

Joint Oceanographic Institute

University of New Hampshire

Scripps Institute of Oceanography

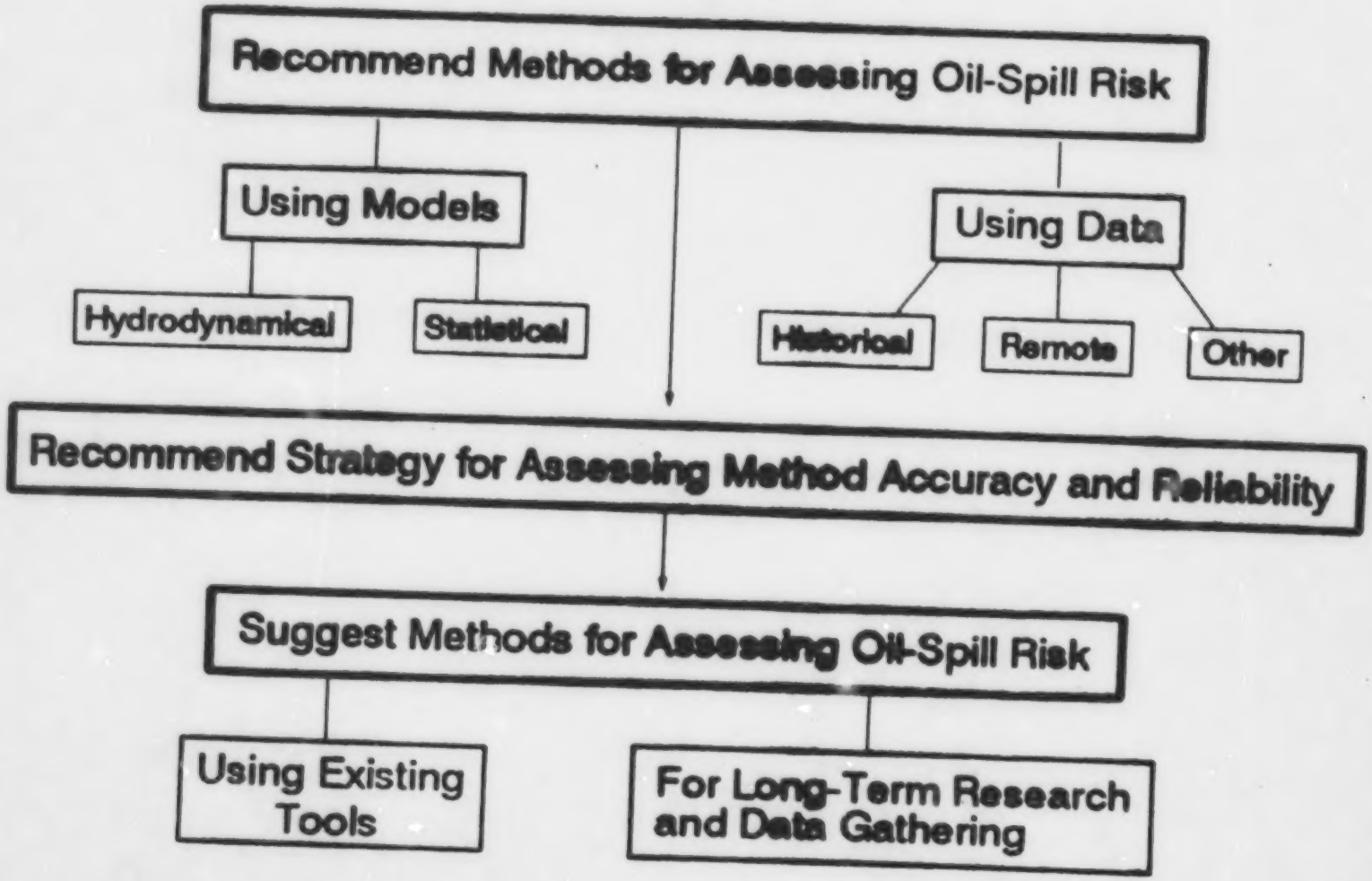
Johns Hopkins University

SUNY - Stoney Brook

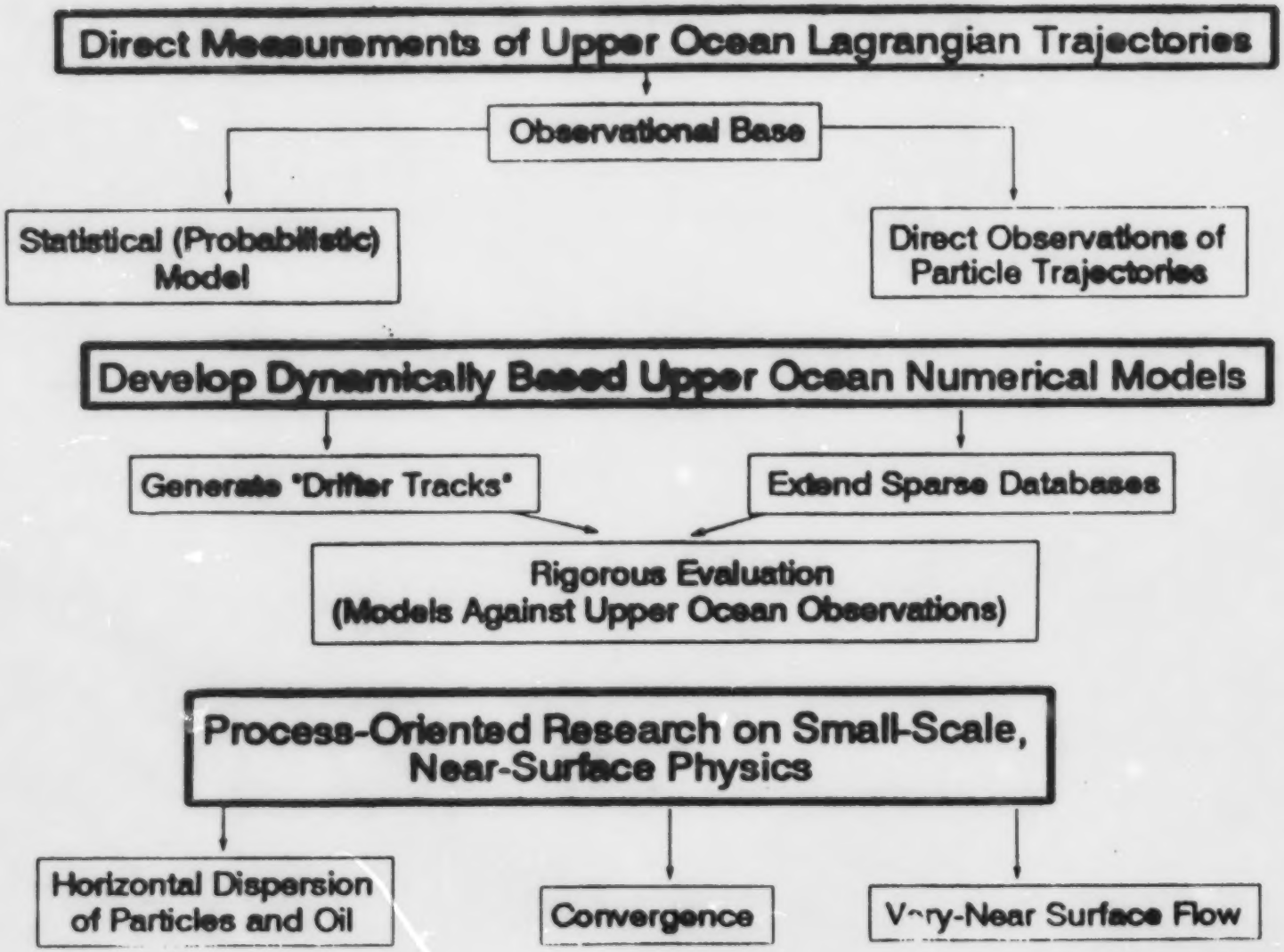
Old Dominion University

Cornell University

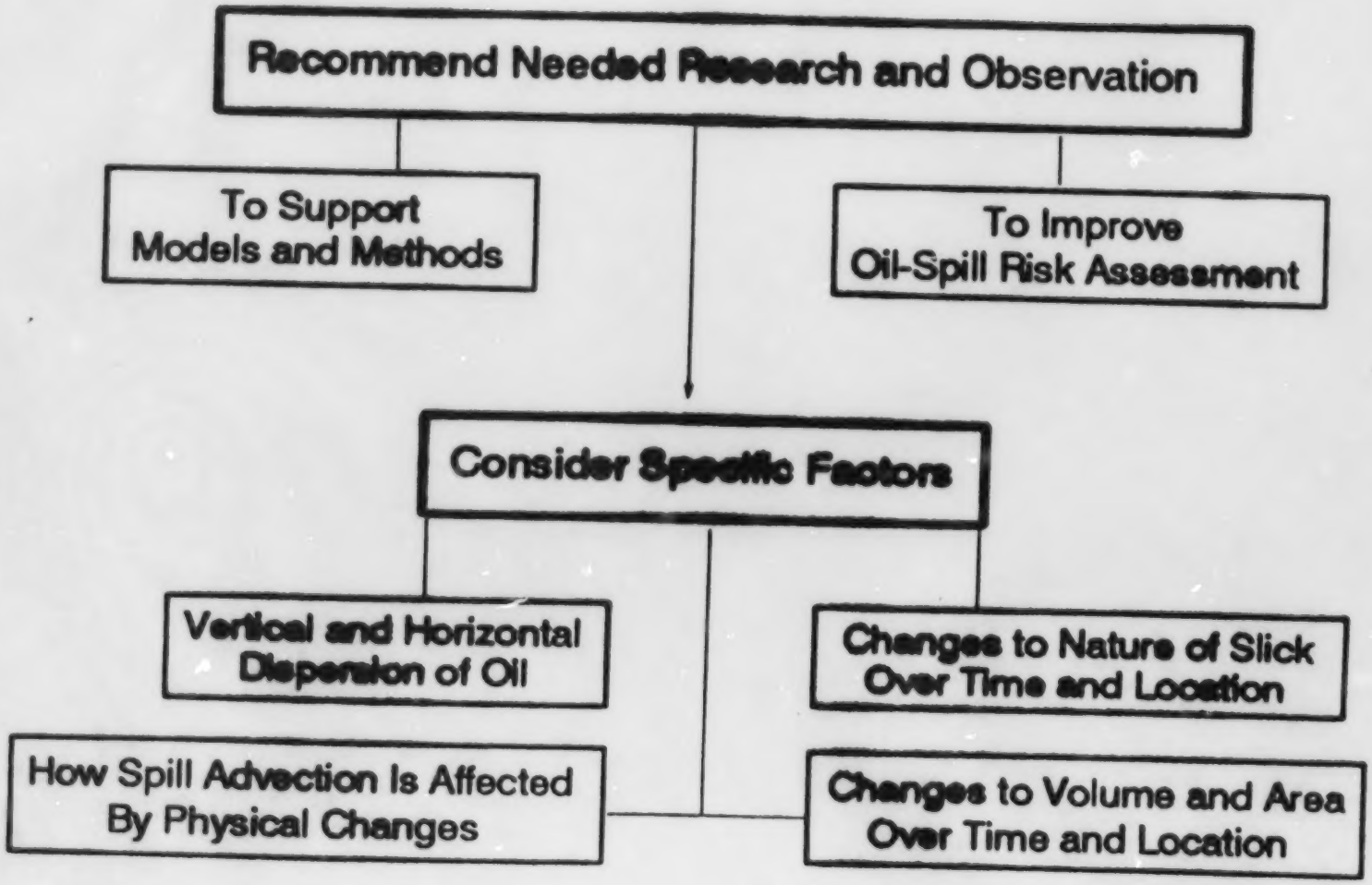
WORK GROUP CHARGES
OIL-SPILL TRANSPORT



OIL-SPILL TRANSPORT
WORK GROUP RECOMMENDATIONS



WORK GROUP CHARGES
OIL-SPILL FATES



OIL-SPILL FATES
WORK GROUP RECOMMENDATIONS

Short Term:

1. Link Fate and Trajectory Models, When Possible

2. Assimilate New Process Knowledge Into Models, As Available

3. Compare Alternative Algorithms for Spreading & Fates

Long-Term Field Studies:

1. Oil Spill-Upper Ocean Interaction

   Vertical Dispersion
   Horizontal Spreading
   Oil Droplet Size & Distribution
   Convergence Zones

2. Oil Spill-Shoreline Interaction

   Nearshore Physics
   Beach Composition
   Weathering on Shore Face

OIL-SPILL FATES
WORK GROUP RECOMMENDATIONS

Long-Term Model and Method Development:

1. Consider Other Concepts for Spreading Models
2. Develop Predictive Models for Emulsification and Mousse Development
3. Develop Remote Sensing of Oil-Slick Thickness

OIL SPILL TRAJECTORY MODELLING
USERS PERSPECTIVE

(Abstract Only)

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St. John's, NF

Oil Spill Trajectory Modelling must serve many uses and many users.

Planning. Oil spill trajectories are used during the development of spill countermeasure philosophies and contingency plans and associated activities such as equipment acquisition planning and spill response training. To be truly useful, the models must be compatible with resource sensitivity mapping for the area. Spill trajectories also influence the design of monitoring programs.

Operations. To be useful for operations, spill trajectory models must be able to respond to a constantly changing situation i.e. use both theoretical and empirical data; respond to different specific questions; and be able to be used by a range of users, in the field, at the command base and in scientific laboratories.

Trajectory models should be able to help answer a wide variety of questions during a spill - for example:

- on the spot operational decisions
- public information and media packages
- tactical information for the fishing industry
- establishment of closed zones

Post-Spill Assessment. Potential post-spill uses for spill trajectory models include spill damage claim negotiations (biological and economic), post-spill monitoring, further response training, reassessment of spill contingency plans and so on.

TRAJECTORY NEEDS AND REQUIREMENTS OF THE FEDERAL-ON-SCENE-COORDINATOR

(Abstract Only)

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During a spill event the United States Coast Guard's Federal-On-Scene-Coordinator (FOSC) requires information concerning the spread and movement of the spill. This information is developed by the NOAA Scientific Support Coordinator. The depth and detail of the information required varies during the course of the spill. Initially the FOSC requires an estimate of the initial speed and direction of movement of the spill. This is critical information which enables the FOSC to quickly mobilize the available response resources. As the spill progresses the FOSC requires more detailed information in order to plan adequately for response. This information would include which beaches/shoreline the spill will impact and when, and where are the heaviest concentrations of oil on the water. These changing needs and requirements of the FOSC must be fully developed in order to create the operational tools required to forecast the spread and movement of the spill. It is also important to realize that forecasting models alone cannot provide the necessary information for the FOSC. Other tools used during the spill such as surveillance must be integrated into the forecasting system in order to provide the best information to the FOSC.

OIL SPILL TRAJECTORY MODELS - RESEARCH AND DEVELOPMENT NEEDS

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INTRODUCTION

The ability to look into the future has been a compelling goal of mankind from time immemorial. The initial developments of these technologies used goat entrails or snake's tongue, these rather primitive methods were eventually replaced by Tarot cards, tea leaves and crystal ball gazing. All have proved equally effective. As mankind developed improved science and technologies, attempts to predict the future depended on the development of equations to describe the motion and interaction of systems. Such predictive techniques have been very successful in simple, large scale systems. During the early part of the twentieth century it was realized that there were limitations to this simple predictive theory at atomic and nuclear size scales. Thus small scale systems must be described in terms of the probability of an event, rather than a causal prediction of the event. Recently it has been shown that the interactions of large complex systems cannot be described in causal terms, but rather eventually such systems become chaotic. While the bounds of chaos can be calculated, even for these systems there is a lack of predictive capability. The prediction of the future state of many natural systems has best been described by Chaos Theory, rather than causal theory. This imposes a significant bound to the ability of models to predict future system states.

NEED FOR OIL SPILL MODELS

The response to an oil spill incident is a complex situation. The mobilization and deployment of equipment is a time consuming task. In order to optimize the effectiveness and efficiency of an oil spill response function, it is highly desirable to have an understanding of the probable position of the various components of the oil spill in the future. For operational purposes, this time scale is of the order of a day or two, while for planning purposes the time scale is days to weeks. The only way to make such predictions is by the use of a trajectory model. This very real need has lead to the generation of a number of models for use by various response agencies. These models are generally called "real-time" or "operational" models. Since during an oil spill response the output of the model is generally verified by actual observations, the errors associated with the model system are readily observable.

As a component of the determination of the environmental impact of a potential oil spill, oil spill models can be used in a "scenario" or "predictive" fashion. This involves the generation of long time series of the input forcing functions, and the use of a model to predict the impact areas of any potential spill situation. It is impossible to verify the prediction of such a model activity except by comparing the results with those of another model.

Both types of models use similar basic equations and have similar input needs, but have very different criteria in terms of computational time and efficiency and quality of output.

DEVELOPMENT OF AN OIL SPILL TRAJECTORY MODEL

The development of an oil spill trajectory model is quite simple. Basically you need to understand the concepts of vector addition. The advection components of an oil spill are the ocean current fields of the area. These are a combination of wind-driven surface current fields, the tidally driven ocean currents and the long term residual or season ocean currents. These are added vectorially to produce the basic driving forces that move the oil slick. The spreading of the oil is described by a number of equations, such as those derived by Faye. A combination of the motion and spreading determine the simple motion of the oil.

The weathering processes have been widely described in the literature and these algorithms are readily available. Since only the rapid weathering process have any impact on the predictions of the model in the short term, the number of weather parameters can be limited to evaporation, emulsification and dispersion.

Given the availability of suitable data, it is easy to develop a computer-based oil spill model. If you are over forty or are a scientist or engineer you would use Fortran or Basic. Those who have taken a computer science course will naturally use a structured language such as C, and the more sophisticated will make a claim for C + + or a similar object oriented language. Various factions will favour Apple or DOS based systems and decry the limitations of these personal computers. Many advanced users will opt for the use of UNIX on an engineering work station. The basics of the model remain the same, and the final prediction is largely independent of the nature of the coding used or the platform used to run the model.

The differences between the more than two hundred oil spill models are generally in the ease of use of the model and the quality of the output data. Models with limited capability but with a high quality output are generally more popular than the arcane model with scientifically correct algorithms.

For operational purposes, the dominant requirement for the model is to generate an easily understandable output using a minimum of input data in a timely fashion. This means that much of the complexity of an oceanographic and geographic area must be pre-stored in the computer, so that a trajectory can be developed for use quickly.

MODEL INPUT PARAMETERS

In order to predict the motion of an oil spill, a set of input data is required. As with all computer models, the statement "garbage in--garbage out" applies to the oil spill model situation. In many spill situations, the oil quickly spreads over a large area, and this demands that data be available not only to the immediate area of the incident, but for a larger area to which the oil may spread. The extended data coverage is larger than the oil area, since the model needs to cover an area much greater than the oil.

The various types of data can be divided into a number of categories:

1. Driving Forces
2. Oil Properties
3. Spill Characteristics
4. Description of Geographical Area

1. DRIVING FORCES

The motion of the oil is determined by the ocean surface currents in the area. The various components of the ocean currents are:

a. The wind induced surface current which is generally 3% of the wind speed. In order to calculate these currents, the spatial distribution of wind speed and direction must be known, both at the present time and into the future. Orographic effects will modify the local wind field and are very important in the development of the surface current field.

b. The prediction of the tidally driven currents requires a knowledge of the present and future tide heights, and a method of translating the temporal variation of water height into surface currents. This involves a knowledge of the bathymetry of the area.

c. Data on the seasonal or long term ocean currents can generally be obtained from oceanographic studies of the area. These currents form a background advective driving force, and need only be entered once as a spatially variable map.

2. OIL PROPERTIES

The standard oil properties such as API gravity, density and viscosity are readily available, and are needed for input into an oil spill model. There are a number of other parameters that are needed to describe the weathering processes that are not generally available for many crude oils. Different models require different types of oil parameters. The simplest models use empirical constants for most of the weathering processes. The determination of these constants requires undertaking specific laboratory experiments on the oil types that might be spilled. This would seem to be a useless activity, since the laboratory measurements can be directly used as an input to the model.

Most sophisticated models use boiling point fractions or similar descriptions to characterize the oil. Unfortunately there is no standardization on the selection of these fractions, and therefore the input parameters needed to characterize the oil are unique to a particular model situation.

The process of emulsification is very poorly understood, and no method has been identified that realistically describes this mechanism.

3. SPILL CHARACTERISTICS

The spill characteristics form a source term for most models. The critical parameters are the rate at which the oil is being released, and the total release time. For most spill situations, these numbers are very difficult to obtain, and there is a tendency to underestimate the total volume during the initial phase of the spill.

For a tanker spill, the best volume estimates can be obtained by ullage of the tanks, while for a blow-out it is almost impossible to directly determine the volume of oil released .

4. DESCRIPTION OF GEOGRAPHICAL AREA

A digitized map of the area is needed on which the results of both the model predictions and surveillance overflights can be plotted. The scale needed depends on the size and location of

the spill, but scale of 1:100,000 to 1:25,000 have been found useful for most spill situations. There is a lack of digital maps for most areas of the country, and hence it is frequently required to digitize charts as needed during an oil spill response effort.

OIL SPILL MODEL COMPUTATIONS

The basic computational aspect of any oil spill model is contained in a central core or "kernel" . Most models divide the total spill into a number of small particles or "spillettes" and the model space in a grid which covers the model area. The model computes the changes in the motion and characteristics of the oil in a series of time steps based on the input data and its internal algorithms. The data from these computations is stored and then rearranged by the output module for display. The functions of this module can be divided into an advection component and a fate or weathering component.

1. ADVECTION COMPONENT

The advective component uses the vector addition of the wind and ocean current information to compute the motion of the oil. The fundamental processes are well understood, and the errors in these computations are generated by the lack of precision of the forecast wind fields. Orographic effects can play a major factor in many areas and are difficult to compute. The basic limits of chaos theory define the accuracy of the longer term predictions of the wind field. At the small scale, models have been unable to predict the existence of wind rows, even though these features are a common reality in all spill situations.

In many areas of the country, there are only limited oceanographic data sets and very few of these have been analyzed to produce 2-D current fields over a large area. While the use of 3-D models has the potential to provide a translation of the tidal parameters to current fields, these models require extensive computer power and are not very useful in the spill situation.

The spreading of the oil is computed using oil properties and equations that describe this process. One of the issues with spreading in many models is developing a mechanism to generate the observed thick and thin oil regimes. The stopping of the spreading process which is observed has not been successfully modeled.

The advective computation occurs at every grid point for every time step, and hence generates a large amount of data. The computer must recognize the presence of shorelines and deal with the beaching of the oil in those areas.

2. SHORT-TERM WEATHERING PROCESS

The algorithms for most of the fate process are not based on any fundamental understanding of the process and are generally simple linear equations which use a mass transfer coefficient. This implies a simplicity of the process which is generally not realized in an actual spill situation. The main short term weathering processes that are important are:

a. Evaporation

There is a very large amount of literature available on the evaporation of oil and this should be one of the better understood processes. Despite this extensive knowledge base, many oil spill models use a simple parametric approach which is only applicable to a few crude oil types. In some models, the equations are simply

incorrect.

b. Dispersion

There is little basic understanding of the processes of dispersion of oil and how it is related to oil type, wave spectra, or near-surface vertical circulations. Most models use a simple linear parametric approach, and the user is given the opportunity to define the appropriate constants.

c. Dissolution

While dissolution of the various components of oil is well understood from laboratory experiments, this knowledge has not been translated into the algorithms used in oil spill models. The rate of dissolution is controlled by the rate of dispersion. Since dissolution is a small component of the mass balance, it is frequently ignored in the model.

d. Emulsification

There is a limited understanding of this process. There is a significant amount of experimental evidence that the process is triggered by some of the properties of the oil. The parameters that define this trigger point are not well defined, and the rate of emulsification above this trigger point has only been determined on an empirical basis.

3. LONG-TERM WEATHERING PROCESSES

The understanding of the long term fate process such as biodegradation, photo- oxidation and sedimentation is limited, and generally not based on detail observations or experimentation. Most models either ignore these processes entirely or use a simple linear equation with arbitrary rate constants.

OUTPUT

There is little to choose between the various models in terms of their input requirements and the basic algorithms used in the computation of the advection and weathering components. The first impression of most models is their output. Many of the early models used a tabular form of output, which was difficult and time consuming to interpret. These models were generally run on non-dedicated computers whose output was a line printer. Most of the contemporary models use a colour display monitor, and present the output as a map. Some programs have a real-time display, but most run the model and subsequently display the results. In many situations the computer display is very easy to understand since it is in colour, whereas the final printed output is confusing since it has been printed on a monochrome printer. For a model to be considered functional at the present time, it should have the following features:

1. GRAPHICAL OUTPUT

The output of the model calculations should be presented in a graphical form. The advection of the oil should be plotted on a regional base map, with the oil-on-water and oil-on-shoreline area clearly indicated. The regional map should have enough labels to orientate the viewer with a minimum of confusion. The weathering process should be plotted as a time-series

with clear and adequate labels.

2. GIS-BASED

While the immediate need for the model output may be operational, there are a number of other clients for this material. In order to meet a variety of users needs the graphical outputs from the model should be available as a computer compatible output in a format that can be easily used by industry standard GIS systems. Some commonly used files types are DXF and CGM files.

3. EASY TO UNDERSTAND

The output of the model should be easy to understand to the user, and should not require interpretation by the person who is running the model. The base map should include adequate place and feature names to orient the user. A north arrow should be on any map, together with a map scale.

The graphical output of the weather calculations should use standard units, which are clearly indicated on the graph. Obscure scales such a as square-root or logarithmic should be avoided. Care should be taken to enable the user to follow the various lines on a graph when it is printed in monochrome and transmitted by Fax.

OPERATIONAL NEEDS

Many existing oil spill models are developed with little reference to the operational needs of the model user. While these models may be technically correct, they fail (when used during a spill) in providing timely and useful data to the spill response groups. It should be remembered that models are a support service and should provide useful information with a minimum of use of support services and manpower. Some of the operational parameters that should be considered are:

1. Ease of use by personnel with a minimum of training.

2. The computer needs should be minimized so that adequate computer power can be available at the scene of the incident. The use of modems is generally not practical due to the demands on the communication system by other spill response groups.

3. Run times are critical in any response. Any model that takes more than 2% of the predicted time to run is probably not useful.

4. The output of the model should be clear and unambiguous. The hard-copy output should be monochrome for ease of making copies and transmitting the data by Fax.

5. The model should have the ability to interchange data with other users by electronic means. This limits file size to those available on standard computer discs.

WHAT ARE THE RESEARCH NEEDS IN OIL SPILL MODEL DEVELOPMENT?

The basic concepts of oil spill models are well developed. The present research needs in computer modelling are limited to improving the physical basis for the fundamental weathering algorithms and utilizing improvements in computational power in an effective manner. Some areas in which research is needed are:

1. There is a need to develop better fate algorithms for all the processes included in a weathering calculation. A better fundamental understanding of emulsification and dispersion is of the highest priority.

2. The computation of tidally generated currents from tidal forcing functions presently uses complex models which require extensive computational facilities and long model run times. These are not useful, and some emphasis should be placed on the development of FAST 3-D oceanographic models.

3. Most existing complex oil spill models are too slow! There should be some effort devoted to the development of methods to increase computational efficiency and effectiveness of existing models.

4. Models should become more outward looking and must produce files that are compatible with existing GIS and data-base systems.

WHAT ARE THE RESEARCH NEEDS WHICH HAVE LITTLE BENEFIT?

The list of research activities that should not be undertaken is very long. A few areas that should be highlighted are:

1. Better wind models.

   The improvement of wind forecast capabilities is a more general public need than for oil spill trajectory modelling. Any improvements made in forecasting accuracy can easily be incorporated into existing models.

2. Spreading

   The existing algorithms are adequate and are limited by the nature of the input data.

3. 2-D ocean currents.

   Present technology is adequate and effort should be devoted to the development of fast 3-D models.

4. Work on Photo and Auto Oxidation.

   These processes are complex and the data is only needed in special circumstances. The present understanding of these processes indicates that the needed input data for any model of this process would not normally be available during a spill.

SUMMARY

There are no big prizes that can be captured by increased oil spill trajectory model research. Most of the effort should be devoted in the consolidation and codification of the current state of knowledge into contemporary models. There are needed improvements in computational speed. The program design should enable new data to be easily incorporated into a model. High quality graphic output and the ability to easily electronically interchange information are important.

OIL SPILL TRAJECTORY MODELLING - PREDICTION ACCURACIES FOR OPEN WATER SPILLS AND OIL SPILLS IN BROKEN ICE, A CONCERN FOR CANADA

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Downsview, On

INTRODUCTION

The primary objective of marine oil spill trajectory modelling is to enable a prediction of where the oil is likely to go and when it will get there. The problem can be further divided into surface and sub-surface travel of the oil. When a spill occurs in ice-infested waters the questions to be posed and answered are increased by an order of magnitude.

In open water spills the drift of the oil is influenced by wind and water currents. The spill motion predictions are directly affected by the accuracies with which these driving forces can be defined. This paper addresses this question and then infers the spatial and temporal resolution and accuracy that can be expected for trajectory predictions.

In cold and ice-infested waters spill motion is further complicated by the type and amount of ice present and also by thermodynamic effects. The paper addresses some of these effects and suggests priorities for research.

OPEN WATER SPILLS

THE QUESTION OF ACCURACY

In open waters the expected travel per day of an oil spill is about 30 km. Thus a 1% prediction error (99% accuracy) will mean the prediction of spill location to within 300 m. If wind was the only variable affecting spill motion then we will need a 99.5% accuracy in each of wind speed and direction to achieve a 99% accuracy in spill location (0.995*0.995=0.99). The present state of wind prediction methodologies clearly precludes such accuracies. Even for a 10% error (3 km) in spill location the wind speed and direction need to be specified with 95% accuracies. If one considers the speed and direction errors in both winds and water currents, i.e., four degrees of freedom, we need ~97.5% accuracy in each parameter to get within a 10% error overall in spill location (0.975**4 = 0.9). The accuracy requirements can be relaxed if one or more of the parameters were to be known to an accuracy greater than 97.5%.

Winds

In the open ocean environment the wind speed (and direction to some extent) is relatively constant over space scales of the order of 100 km. Beyond these scales the spatial variability of the wind has to be taken into account. The temporal variability of the wind can, of course, be quite high even in the open ocean environment. Under such conditions one can expect wind speeds to be specified to within 1-2 m/s or 10% of the speed, whichever is greater and wind direction to within 10-20 degrees. Over a one day travel of 30 km, a 10 degree error in wind direction alone can result in a location error of over 5 km (using $s=r*\theta$).

In coastal areas with complex terrain, the winds generally have preferred directions and hence there is less directional variability. In such cases the emphasis can be on wind speed definition, its variability in time being important. One can expect speed accuracy similar to the open ocean case but the direction accuracy can be better.

Water Currents

Water currents can be divided into tidal and non-tidal components. Once defined using three-dimensional numerical models, the tidal variations are known and speed accuracies close to 2 cm/s (a fairly optimistic value) can be expected.

In the case of non-tidal currents, it is a boundary/initial value problem. Model development is in not yet adequately advanced to be able to predict current speed and direction with sufficient accuracy. At present prediction accuracies are at best in the 60-80% accuracy range.

CONCLUDING REMARKS AND PRIORITIES FOR R&D

In open water, given the present state of knowledge, one-day spill movement forecasts to an accuracy of a few hundred meters is not feasible. An accuracy of about 1-3 km is more practical. A very good knowledge of the non-wind-driven water currents can result in a prediction accuracy near the lower end of this range. In order to provide improved spill movement forecasts emphasis should be on:

- increasing the accuracy of inputs, viz. winds and water currents.

SPILLS IN ICE-INFESTED WATERS

It is a matter of record that a large number of oil spills occur as a result of human error. Given this situation and the fact that a large portion of canadian waters is ice-covered for a good portion of the year, there is a finite probability of an oil spill occurring in ice-infested waters. In fact, a spill occurring in open waters can easily drift into ice-infested waters. It would therefore be prudent to be prepared to tackle such an eventuality. The costs involved in being prepared should be far lower than the penalty for being unprepared.

Oil spills in ice-infested waters can be classified into three distinct categories: i)spills on ice, ii) spills under ice, and iii)spills in broken ice. Past studies have mainly concentrated on the first two categories and have been briefly reviewed by Spaulding (1988) and Venkatesh et al. (1990).

OIL SPILLS IN BROKEN ICE

Oil spill in broken ice is a very complex problem, the additional complexity being mainly the result of different ice concentrations, ice types and floe sizes. The understanding of oil behaviour in broken ice is in its early stages. Venkatesh et al. (1990) have explored the problem and have described some preliminary ideas on how oil spreads under different ice concentrations and ice types. Their study has also established some distinct differences between oil behaviour in warm water, cold (near freezing) water and ice-infested waters. In certain ice concentrations, the relative oil/ice densities have a significant influence on whether oil stays between and under ice floes or rides up on top of the ice. Oil riding up on the ice surface can have a significant impact on the albedo of the oil-contaminated ice surface and hence has the potential for heat absorption and ice melt. A large spill in such waters can then have an impact on the climate of the region. The above

areas need further study.

When oil gets trapped in the roughness cavities on the underside of the ice, it stays there until the water current velocity exceeds a threshold value. Weathering of this oil is considerably slowed down by the cold temperatures. Depending on the time of year of the spill, the oil can remain trapped under the ice for a long period of time. Thus even if weathering proceeds at a slow rate, given sufficient time the oil can weather resulting in a change in its density. At some point, if the oil becomes heavy enough to become detached from the underside of the ice, its movement will then be dictated by the current velocity and not by that of the ice. Thus there is a need for data on weathering of oil under cold temperature conditions.

Another question that needs to be addressed is the nature of the relative oil/ice drift in a range of ice concentrations. While observational data show that the relative oil/ice drift is negligible over short periods of time (of the order of a few hours to a day), the behaviour over long periods is not certain.

PRIORITIES FOR R&D

Based on the above discussion, the following are suggested as priority areas for R&D in respect to oil spills in ice-infested waters:

1. To improve understanding of how oil spreads in different ice concentrations and ice types. In the event of a spill the relative oil/ice densities can affect the albedo of the surface which in turn can affect ice melt rates.

2. To gain better knowledge of impact of weathering on oil moving away from the underside of the ice.

3. To improve understanding of the relative oil/ice drift over long periods of time (> a few days).

4. To study the processes of oil encapsulation and other thermodynamic effects of oil/water/ice interaction.

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VERIFICATION OF PAST MODELLING EFFORTS - MMS

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The Oil Spill Risk Analysis (OSRA) model of the U.S. Minerals Management Service (MMS) is used to help estimate the environmental hazards of developing oil resources in offshore lease areas. A stochastic analysis of potential spill trajectories is used to evaluate risk over the 18- to 30-year lifetimes of planned offshore production and transportation of oil in Federal waters.

Verifying that thousands of trajectories simulated over wide ranges of environmental conditions are correct or reasonable is a challenging task. Making a formal error analysis is complicated by the unknown error of the information used as input to the model, such as circulation model output and wind-field data. The reliability of the OSRA model is assessed by evaluating individual model components to ensure correct performance, investigating the sensitivity of model results to particular assumptions, and comparing model results with actual oil-spill trajectories and other appropriate observations.

The OSRA model output frequently has been compared to observation of oil spills (Amstutz and Samuels, 1984). Since the model results are a probability distribution, one purpose of such comparisons or "hindcasts" is to evaluate to what extent the envelope of OSRA trajectories included the actual observations.

After the Argo Merchant spill there was sufficient wind and oil slick location data for hindcast purposes (LaBelle, et al, 1984). Beginning with the date of the initial spill, eight trajectories per day were simulated from the vessel grounding site, for eight days. The surface water velocity fields were provided by the Dynalysis of Princeton circulation model. The OSRA model was run using the time series of the observed winds at the Nantucket light ship, using real-time winds to initialize a statistical wind model, and initializing the statistical wind sampling with seasonal wind statistics. The simulations, in general, reproduced the observed drift of the Argo Merchant oil spill, including no contacts to land. Less variability in results was shown when the real-time wind record was used.

Although simple qualitative hindcasts are routinely run, the problem of statistically verifying a simulated Lagrangian path is, as yet, unsolved. It is not sufficient to compare one Lagrangian path (such as a model simulation) against another (such as an actual oil spill trajectory) because both are incidental evidence of a small part of the Lagrangian field over a limited space and limited time. The MMS is presently researching the statistical verification of Lagrangian paths or trajectories. Presently, the OSRA model results are scanned for consistency and reasonable behaviour through animation and visualization routines on a Silicon Graphics workstation.

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LaBelle, Robert P., W. Samuels, and D. Amstutz, 1984. An Examination of the Argo Merchant Oil Spill Incident Using a Probabilistic Oil Spill Model, Presented at the 47th Annual Meeting of the American Society of Limnology and Oceanography, Vancouver, B.C., June 11-14, 1984.

OSRA -- A TOOL FOR ESTIMATING:

Chances of offshore oil spills occurring

Where spills are likely to go

Resources that spills might contact

DEFINING MODEL SKILL

What is "correct" function of:

Time
Scale

What data can be used to define skill?

Historical
Experimental
Statistical (observations/data distillation)

Problem: Oil does not strictly behave as a surface following drifter

Oil-following drifter under development

*ARGO MERCHANT SPILL CHRONOLOGY

DATE	EVENT
DECEMBER 15, 1976	ARGO GOES AGROUND ON NANTUCKET SHOALS AT 0600 HOURS.
DECEMBER 16	FIRST VISIBLE SLICK, SHIP EVACUATED.
DECEMBER 17 - 20	1.5 MILLION GALLONS ESTIMATED SPILLED OVER THE PERIOD.
DECEMBER 21	HEAVY SEAS CAUSE SHIP TO BREAK IN TWO AT 0845, APPROXIMATELY 70% OF THE OIL CARGO SPILLED (5.5 MILLION GALLONS).
DECEMBER 22	*BOW SECTION SPLITS AGAIN.
DECEMBER 29	BOW SECTION MOVES UNDER INFLUENCE OF CURRENTS.
FEBRUARY 8, 1977	BOW EXAMINED AND FOUND EMPTY OF OIL.

*(REF: THE ARGO MERCHANT OIL SPILL, A PRELIMINARY SCIENTIFIC REPORT, NOAA, U.S. DEPT. OF COMMERCE, MARCH 1977.)

SPECIFIC INPUTS TO THE MODEL

SURFACE CURRENTS:

REPRESENTATIONS OF THE MONTHLY SURFACE WATER VELOCITY FIELDS WERE PROVIDED BY DYNALYSIS OF PRINCETON, USING THEIR CHARACTERISTIC TRACING MODEL. (KANTHA, 1981).

WINDS:

SEASONAL WIND TRANSITION MATRICES WERE CALCULATED FROM THE U. S. WEATHER SERVICE RECORDS FROM NANTUCKET SHOALS WEATHER TOWER.

REAL-TIME WINDS WERE RECORDED FROM THE NANTUCKET USCG LIGHT SHIP, ANCHORED NEAR 40 DEG. 30 MIN. N LATITUDE, 69 DEG. 29 MIN. W LONGITUDE, CLOSE TO THE SOUTHEASTERN EXTREMITY OF THE SLICK.

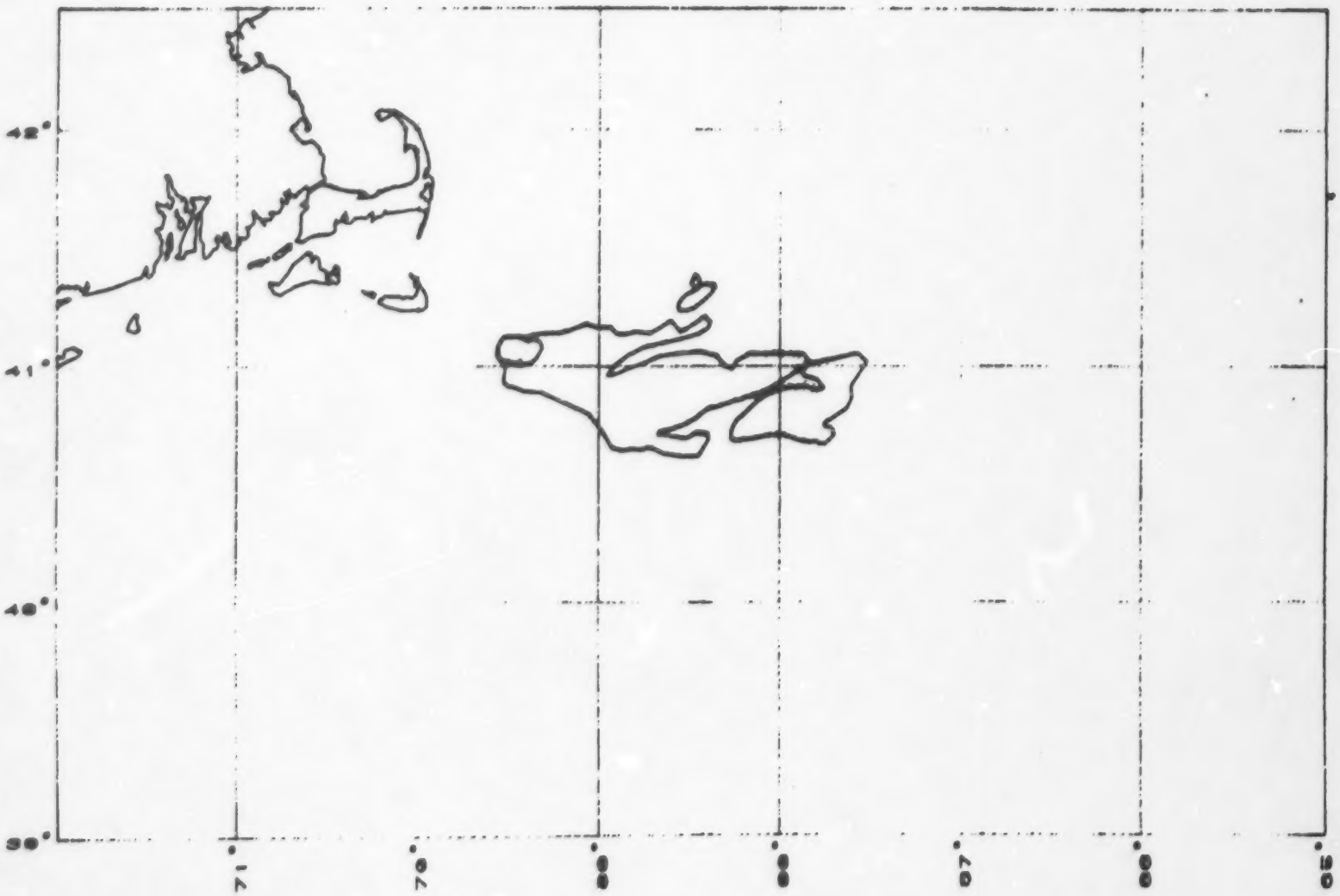
SIMULATIONS:

TRAJECTORIES WERE LAUNCHED FROM THE ARGO GROUNDING SITE AT A RATE OF 8 PER DAY, OR EVERY 3 HOURS, BEGINNING WITH WINDS RECORDED AT 0100, DECEMBER 16, 1976.

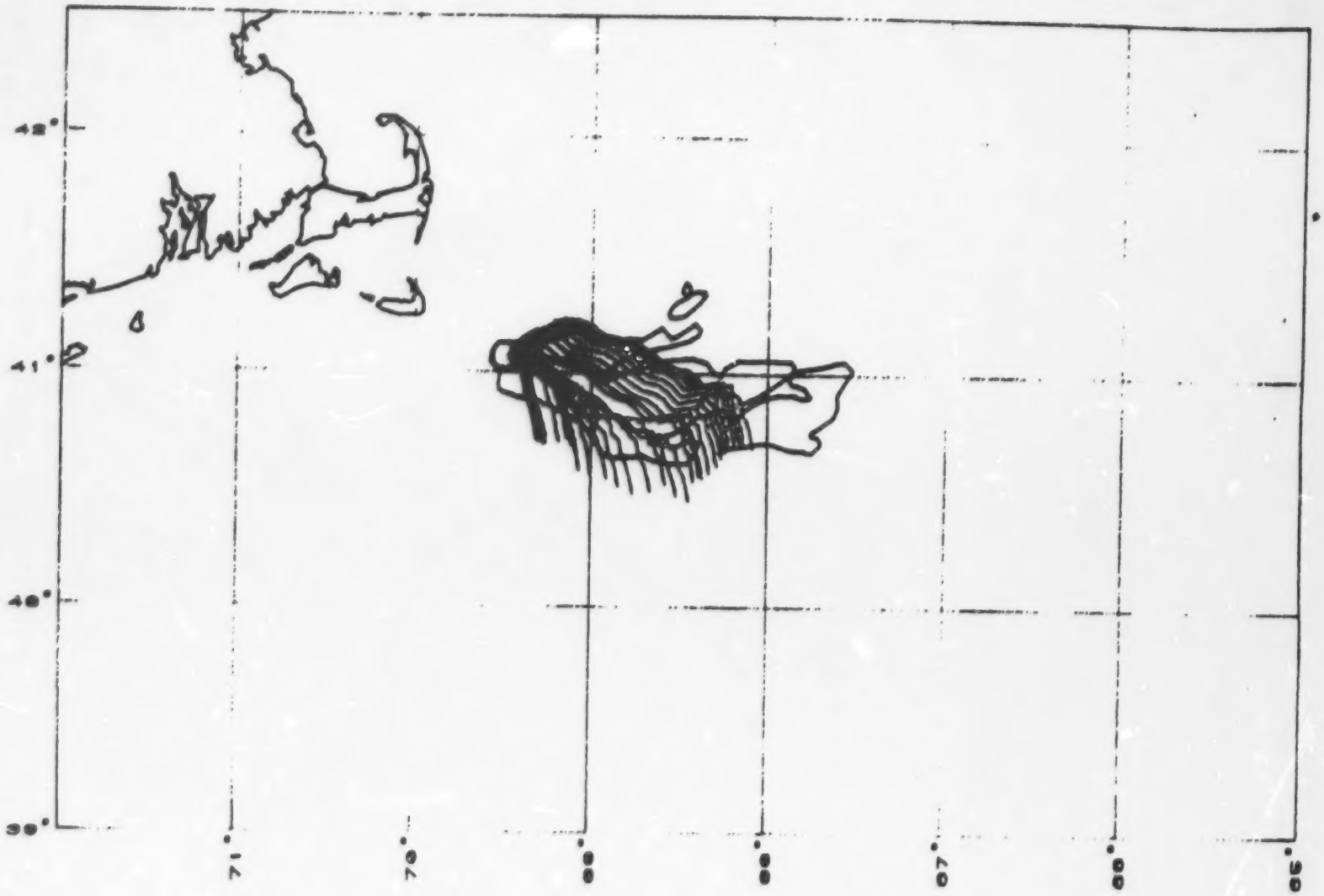
A) THE REAL WINDS RECORDED AT THE NANTUCKET LIGHT SHIP WERE USED TO INITIALIZE THE WIND TRANSITION MATRIX FOR THE WINTER SEASON.

B) THE TIME SERIES OF OBSERVED WINDS AT THE NANTUCKET LIGHT SHIP WAS USED TO MAKE DETERMINISTIC SIMULATIONS OF SLICK TRAJECTORIES.

C) THE WIND TRANSITION MATRIX WAS INITIATED ACCORDING TO WIND STATISTICS FOR THE WINTER SEASON, AS IN STOCHASTIC MODEL RUNS.

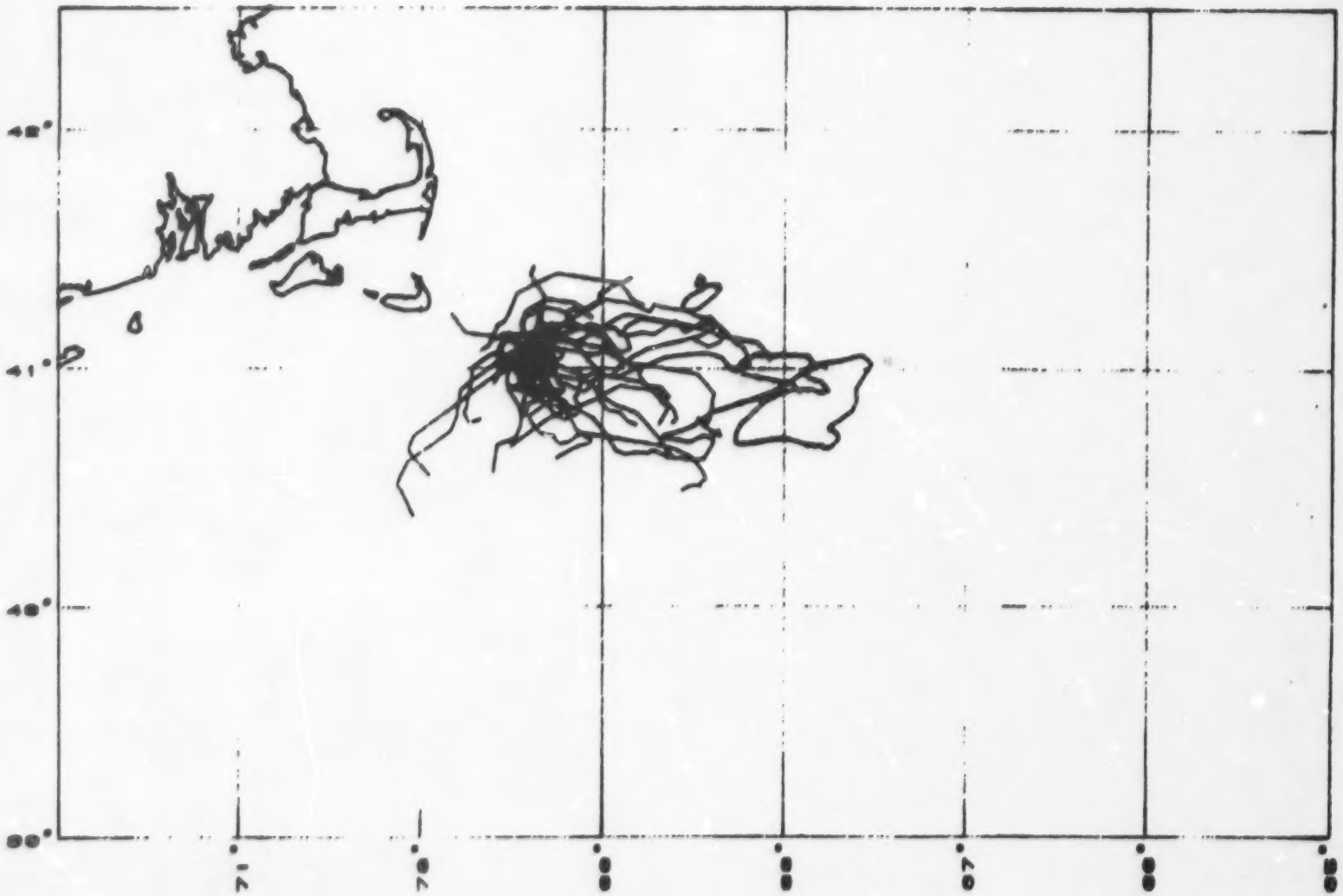


DECEMBER 23



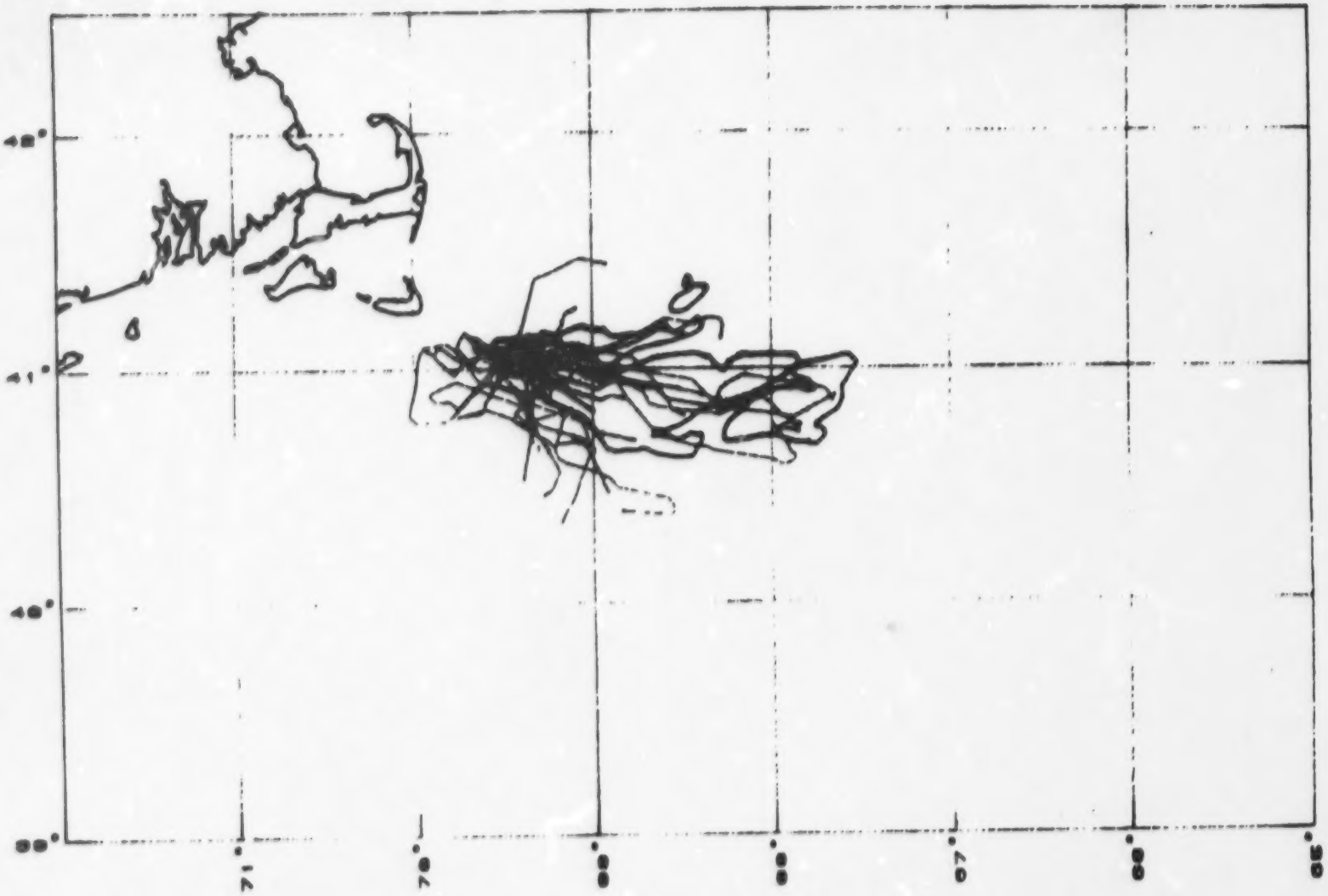
TS20.DAY5

SLICK23

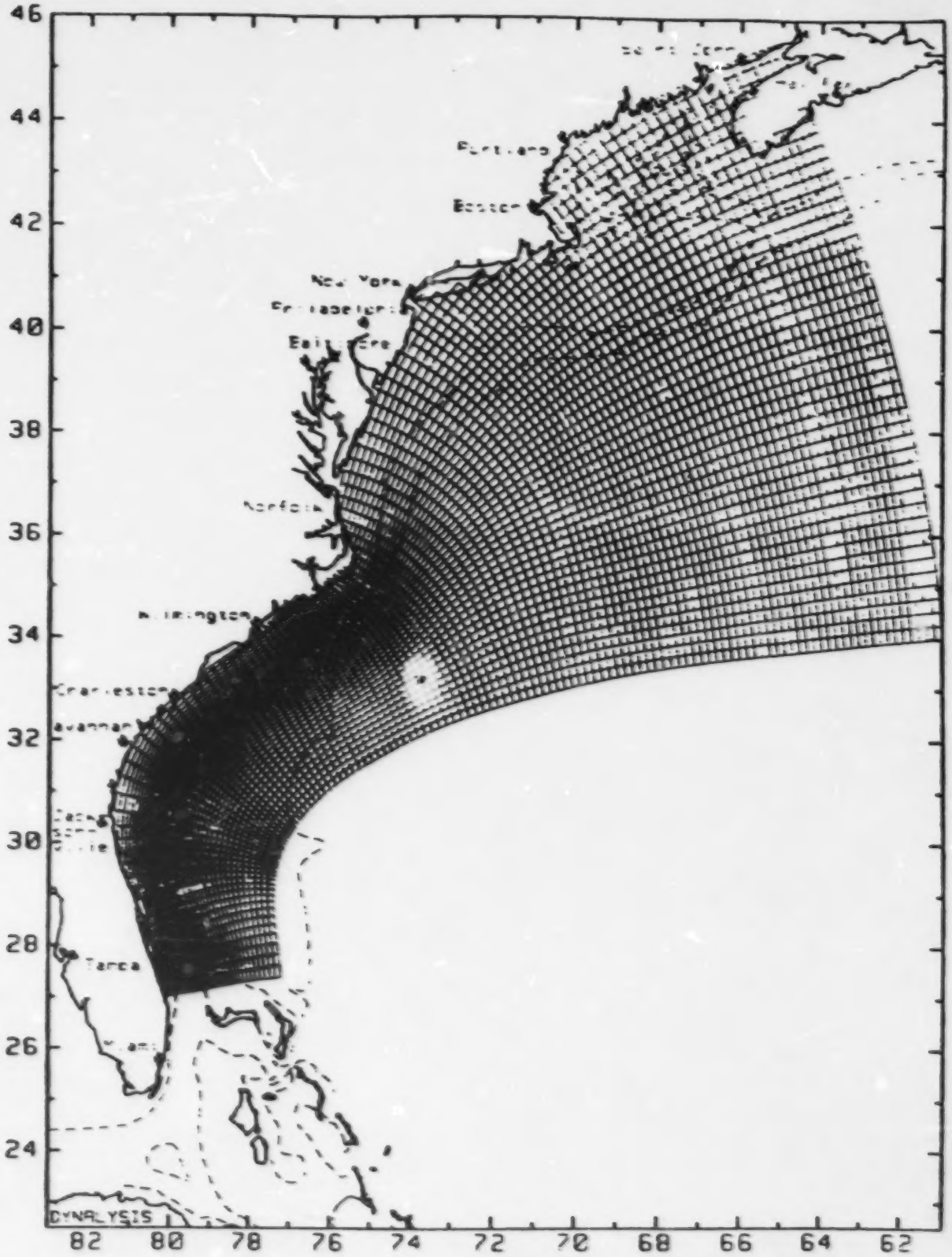


INIT20.DAY5

SLICK23



32 TRAJECTORIES
INITIATED RANDOMLY IN WINTER SEASON
RUN FOR 5 DAYS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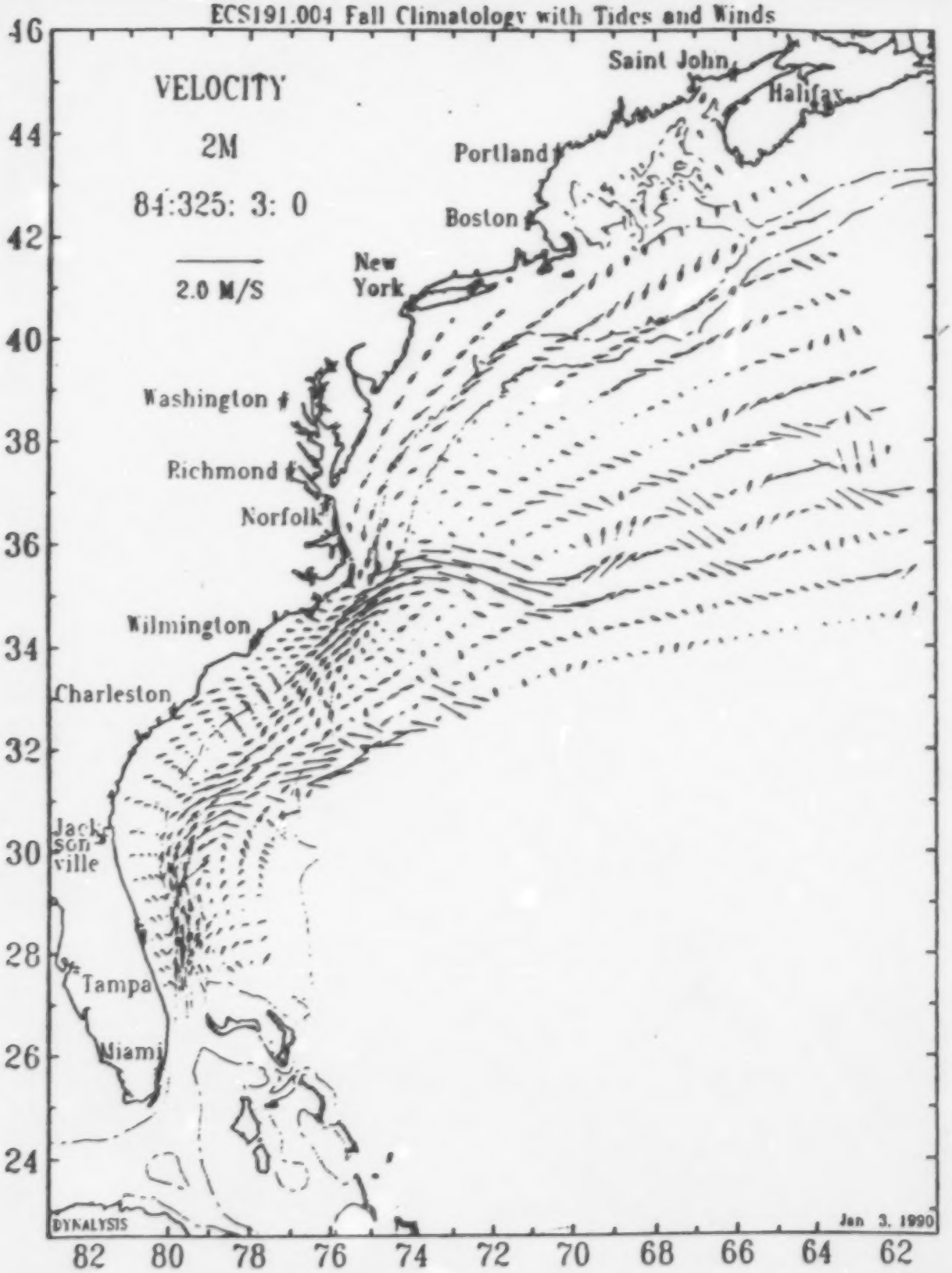
Miami
DYNALYSIS


ECS191.004 Fall Climatology with Tides and Winds
VELOCITY
2M
84:325: 3: 0
2.0 M/S
Saint John
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Portland
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DYNALYSIS
Jan 3, 1990
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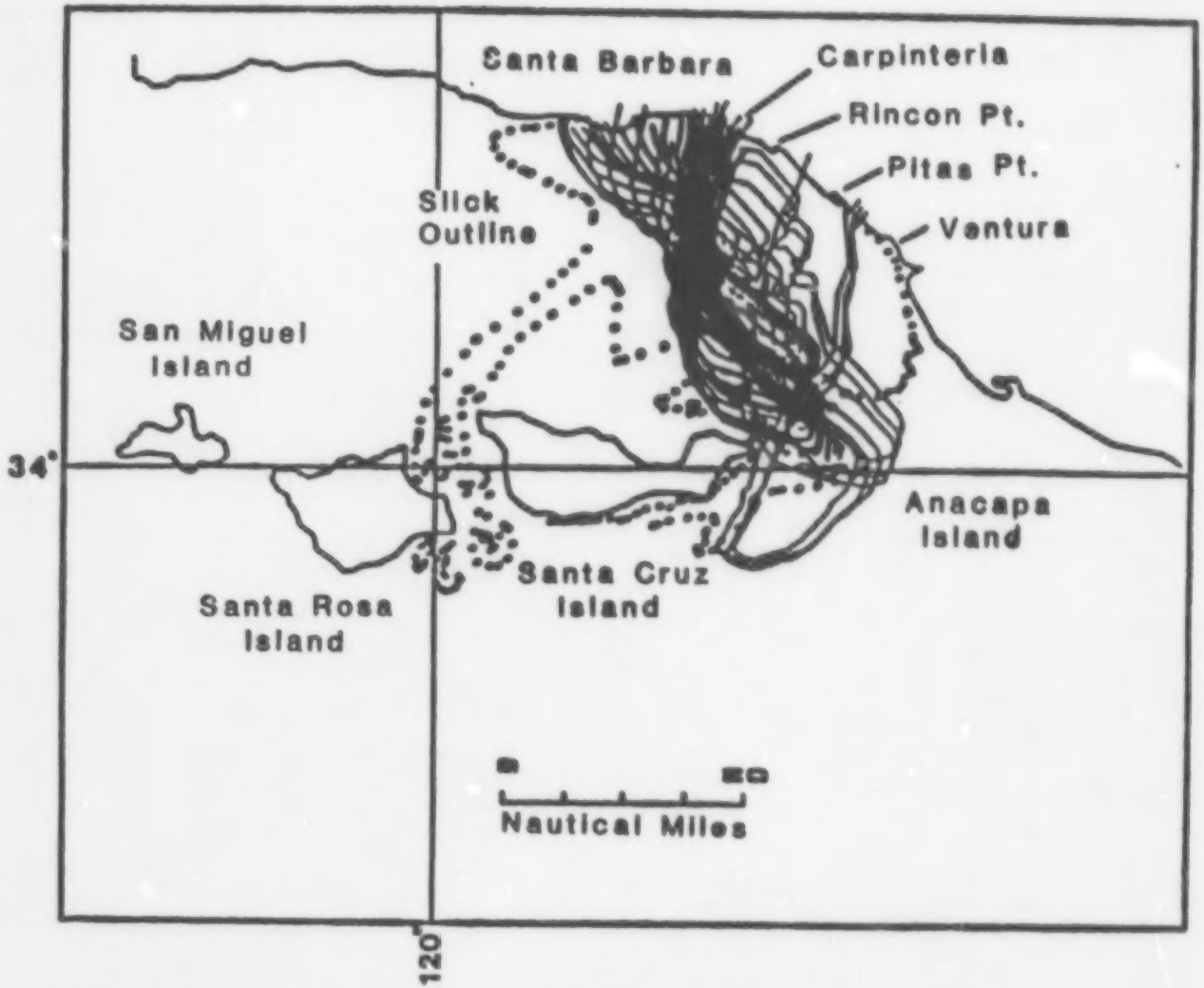

Map of Santa Barbara Channel showing observed slick outline after 8 days, and the sequence of 64 simulated trajectories launched from Platform A at 3-h intervals.

SATELLITE OCEAN ANALYSIS RESEARCH

(Abstract Only)

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Spill response is focused on efforts to control, treat and recover oil before shorelines are affected. Oil-on-water countermeasures are first priority activities that require assessment of sea surface motion for operational decisions and response management.

Predictions of oil trajectories are now based on flow fields calculated as kinematic combinations of historical mean currents and time-dependent wind drift. The potential for inaccuracy is high because, at space and time scales pertinent to spills, actual circulation features rarely correspond to the smooth flow regimes produced by mathematical averaging procedures.

Sea surface motion in the spill-relevant dynamic range is normally dominated by pervasive turbulence with episodic, often chaotic, behaviour. Analyses based on remotely-sensed observations and time-dependent circulation models can deliver accurate estimates of flow fields that approach real-time portrayals at the spatial and temporal scales appropriate for spill response.

Cases are given for the Gulf of Mexico, Mid-Atlantic Bight, and California Current regions that compare trajectory analyses for mean flow fields and synoptic (24 hour), satellite-derived, advective flow field estimates at submesoscale (order 15 km) resolution. The accuracy at which satellite surface flow fields can estimate synoptic, advective displacements is shown by comparison of simulate paths with 22 ARGOS drifter (drogued to 2.7 m) trajectories in the northwestern Gulf of Mexico. The water parcel simulated paths are calculated, without external forcing, by a fourth-order Runga-Kutta integration procedure that uses dynamically-adjusted, satellite sea surface flow fields.

DATA ASSIMILATION AND SHELF CIRCULATION

(Abstract Only)

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One of the major difficulties in modelling shelf circulation is the specification of open boundary conditions; it is usually impractical to measure the open boundary conditions directly and it is difficult to infer them from larger-scale models in which the shelf circulation model is embedded. Although radiation boundary conditions allow internally-generated disturbances to radiate away, the modeller still has to provide the background state - the forcing - about which the radiation occurs. Recently considerable interest has been shown in the use of adjoint models as a way of assimilating data in models of atmospheric and oceanographic circulation (see, for example, the proceedings of the International Symposium on Assimilation of Observations in Meteorology and Oceanography organized by the WMO and held at Clermont-Ferrand, France in July 1990). I will provide a brief overview of this technique and illustrate with results from an assimilation model for the Scotian Shelf which will eventually be used to track larvae on the Scotian Shelf as part of the Ocean Production Enhancement Network, one of Canada's new Centres of Excellence.

VALIDATION PROCEDURES FOR OIL SPILL TRAJECTORY MODELS

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ABSTRACT

The ultimate test of an oil spill trajectory model is to compare its predictions to accurate observations of the fate of a real spill (accidental or experimental). However, the emergency response to an accidental spill is rarely coordinated scientifically, and experimental spills are expensive, time-consuming, and require the coordination of a large multidisciplinary team for success. To focus on the physical processes responsible for drift and horizontal dispersion of the oil, a simpler approach would be to test the model predictions against a large ensemble of trajectories of "calibrated" surface drifters. To calibrate the drifters, 1) their motion (slip) relative to a specified vertical average of the surface water velocity must be measured over a wide variety of wind and seastate conditions, and 2) their motion relative to oil on the surface should be gauged during a limited number of controlled experimental spills. Both procedures require accurate observations of local wind, surface waves and currents. The statistics of large numbers of such trials provide a basis of comparison for similar results from model predictions.

To illustrate the calibration procedures, a series of tests conducted on a number of experimental and commercially available buoys is described. Variations of the test buoy characteristics include mast size, draft and stability. Results indicate that the relative slip between buoys of different type is consistent with a static force balance. However, consistent differences are found between low (inshore trials) and moderate (offshore trials) seastates.

INTRODUCTION

The ideal calibration procedure for an oil spill trajectory model is to compare its predictions against observations from a large number of real spills, accidental and/or experimental. The problem with this is that it is difficult to make systematic measurements of a real spill while operating in a response mode, and experimental spills are expensive and time-consuming. Furthermore, the sensitive areas that are most at risk are the least acceptable sites for large controlled spills.

A solution to this dilemma would be a two-stage approach in which 1) a large number of intercomparison trials were conducted between models and *calibrated* surface drifters, and 2) drifters and model results were compared against the observed behaviour of a limited number of experimental spills. Both activities would require accurate measurements of wind, waves and near-surface currents. Furthermore, observations during the controlled spills must distinguish the rates of drift of the oil under the continuous influence of weathering, submergence, evaporation, etc. After careful analysis, model skill could be assessed against the statistics of the drift and dispersion of the buoy clusters in a large number of coastal ocean settings. With sufficiently accurate observations, differences in model skill should be attributable to model physics and capability. Finally, the performance of the buoys could be matched to that of the experimental spills so that they could be utilized to aid in tracking oil under operational conditions.

Some early attempts at Bedford Institute of Oceanography (BIO) to calibrate a suite of surface drifters for wind loading and vertical current shear are described below. Affectionately known as the "fish barrel" buoys, these drifters are the forerunners of the SEIMAC Accurate Surface Trackers (AST). With regard to performance, these buoys are not optimal since they do not follow the surface very well and have relatively large resonant periods (2-3 sec) of heave, pitch and roll. However, it is the calibration technique, not the results, which are to be illustrated here. The same method could and should be applied to other better-designed surface drifters.

BEDFORD BASIN TRIALS

Two sets of trials were conducted to evaluate the performance of the BIO buoys. The first set was carried out in Bedford Basin and included a number of commercially-available buoys with a wide variety of shapes and sizes (Figure 1; Elliott, *et al*, 1983). These trials featured low seastate conditions, since the size (order 2-3 km) and shape of the Basin severely restricted the fetch in all directions. The second set of trials was conducted on the open shelf off Cape Sable, Nova Scotia, under the influence of moderate seastates as well as the strong semidiurnal tidal currents at the entrance to the Gulf of Maine. Discussion of these offshore trials is deferred to the next section.

The BIO buoys designed to provide a systematic variation of the wind and current shear loading at the surface. With a nominal draft of 80 cm, all buoys were ballasted to have an equilibrium freeboard of approximately 2 cm. To vary the wind loading, the diameter of the vertical mast above the waterline was varied by a factor of 12.8 (S,M,L BIO buoys; Figure 1), whereas the effect of surface current shear was assessed by varying the draft by a factor of 4. The ballast of the buoys was also varied (standard 10 kg and 20 kg) while maintaining the freeboard in order to change the resonant periods.

Because of the presence of unknown (i.e. unobserved) currents in the Basin, it was decided to measure the *relative* slip of all the buoys against that of a single standard buoy (small mast, S; Figure 1). If the buoys are not too far separated, i.e. if the surface current may be considered uniform over the region of observations, then the calculation of relative drift removes the effect of the unknown absolute current. With maximum separations of 500-1000 m in water of 50-70 m, this condition is not entirely assured, since the spatial decorrelation in the surface layer is expected to be of the same order as the depth (Geyer, 1989). However, the use of more than one drifter of each type mitigates this effect statistically.

The procedure followed during the Basin trials was to release all buoys simultaneously from an upwind location and then periodically position them using microwave navigation (MINIRANGER) on the ship or by aerial photography. Wind speed and direction was frequently measured from a bow mast on the ship. Sample positions from trial 3 (Figure 2) show the cumulative effects of enhanced wind loading on the M and L buoys relative to the standard, S. The relative drift as a function of time was deduced from the displacement of the centroids of the clusters of like buoys. The relative velocities, DV, were then plotted versus wind speed for each trial and projected out to a 10 m wind speed of 10 m s by linear regression. The medium masted buoys attained a relative slip of 3.9 m/min relative to the small-masted standard (Figure 3a), while the large-masted buoys separated at 6.3 m/min (Figure 3b). Over all trials, the absolute velocity of the small-masted standard buoy was quite scattered, probably due to small scale currents in the Basin, but was generally directed downwind at 2-3 % of the 10 m wind speed (Figure 4).

A static balance between quadratic drag forces exerted by the wind and average surface current on the buoy gives rise to the following expression governing the slippage of the buoy due to wind:

$$(F - R)^2 = K(1-R)^2$$

where $R = U_b/W = (K^{1/2} + F)/(1 + K^{1/2})$ = slippage factor,
and $F = U_s/W$ = wind drift factor,
with U_b = buoy speed, W = wind speed, and U_s = surface current.

For $K = \rho_a C_{Da} A_a / \rho_s C_{Ds} A_s << 1$, where ρ, C_D, and A are density, drag coefficient and frontal area respectively, the absolute and relative drift are given approximately by,

$$R \cong K^{1/2} + F ,$$

and

$$R - R_o = \Delta V/W = \left(\frac{\rho_a C_{Da}}{\rho_s C_{Ds}}\right)^{1/2} \left(\left(\frac{A_a}{A_s}\right)^{1/2} - \left(\frac{A_a}{A_s}\right)_o^{1/2}\right),$$

where the subscript o represents the standard buoy (S). From this expression it is clear that, under the assumption of a static force balance, the relative slippage between any of the buoy types and the standard buoy should scale as the difference of the square roots of the ratios of the exposed areas above and below the water surface. Similar relations have been used in other studies of drift buoys (e.g. Geyer, 1989).

A summary of the relative drift results for the Basin trials (Figure 5) shows an offset between the wind-loading curves for the 10 kg ballasted buoys (X,S,M,L; X=no mast) and the 20 kg buoys (X',S',M',L'), but nearly equal slopes representing the wind loading sensitivity. The slope of the current shear loading curve (S,1/2,1/4) is much steeper, indicating the strong influence of the surface shear layer on the relative slippage. Results from the commercial buoys were quite scattered and not easily related to differences in their effective draft in the surface layer. But perhaps the most interesting result comes from the single offshore trial (trial #29) conducted in moderate seas off the mouth of Halifax Harbour as a pilot for the later trials off Cape Sable. The wind loading curve for this trial showed a distinctly shallower slope than that of the Basin trials, suggesting reduced slippage in the downwind direction. This result required further confirmation from the Cape Sable trials.

CAPE SABLE TRIALS

A series of offshore trials was conducted in the strong tidal regime off Cape Sable, Nova Scotia during a cruise of the research vessel, C.S.S.Dawson, from 14-27 November, 1984. A number of current measurement programs with overlapping objectives were carried out, including moored current meters, shipborne acoustic Doppler profiling, surface currents by shore-based groundwave radar (CODAR), and Lagrangian surface drifters (with and without drogues) tracked by aerial photography and a bottom-mounted array of acoustic transponders (Smith, et al, 1984; Figure 6). Auxiliary measurements of wind and directional surface waves were obtained from a bow anemometer on the ship and a WAVEC pitch-and-roll buoy moored nearby.

The buoys used for the Cape Sable trials consisted of the full suite of BIO experimental buoys (S,M,L,1/2,1/4), plus a drogued (H) and undrogued (H) Hermes buoy (Figure 7). The BIO buoys were all ballasted with 30 kg this time and the relative slippage was measured from aerial photographs take with the ship standing by and oriented into the wind. Winds during the four trial periods were generally between 10 and 15 m s from the NW (Figure 8) and moderate seas had significant wave heights of 1.5 to 3.0 m. A sample of the buoy distribution during one of the trials on 18 November, 1984, (Figure 9) shows the clusters of like buoys stretched out along the wind direction with the Hermes surface buoy slipping furthest downwind and the drogued Hermes furthest upwind. These results are qualitatively similar to those of the Basin trials, although it was much more difficult to position the buoys from the offshore photographs when breaking waves were present.

A quantitative comparison of relative slippage (Figure 10) shows that the reduced slope of the wind loading curve in the offshore is confirmed by the Cape Sable trials and is independent of the ballasting. [Though counter-intuitive, this result has been found in other studies (e.g. Van Dorn, 1953; Keulegan, 1951) and may be related to either sheltering by the waves or the absorption of wind energy by a growing wave field in preference to the surface current.] Expressed as a percentage of the 10 m wind speed, the observed slippage rates imply that if the standard buoy (S) were found to move downwind at 3.0% of the wind, then the large-masted buoy would move at roughly 3.5% in moderate seastates on the open shelf, and at 4.0% of the wind in sheltered coastal regions. This range represents the observed differences between the motion of the leading edge and that of the centroid of some actual oil spills (Reed, et al, 1988) so that in an operational setting, several different types of buoys could be deployed in a slick in order to track different portions of it over its lifetime. As the oil weathers and submerges, buoys with deeper drafts and weaker wind loading could be deployed to match the changing condition of the oil.

CONCLUSIONS

With regard to the proposal to validate oil spill trajectory models with a combination many surface drifter trials and a few controlled spills, the following conclusions may be drawn:

1) Drifters can be calibrated for wind loading and vertical shear at the sea surface, based on an equilibrium force balance.

2) A different relationship must be used when sea state is or is not present. Slippage appears to be reduced in moderate wave fields.

3) Once buoy performance is understood, large-scale deployments in sensitive areas may be used to test trajectory models (suitably modified to account for buoy behaviour).

4) Differences between model skills should reflect their ability to simulate advection and dispersion by wind and background currents.

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Van Dorn, W. 1953. Wind stress on an artificial pond. J. Mar. Res., 12, 249-276.

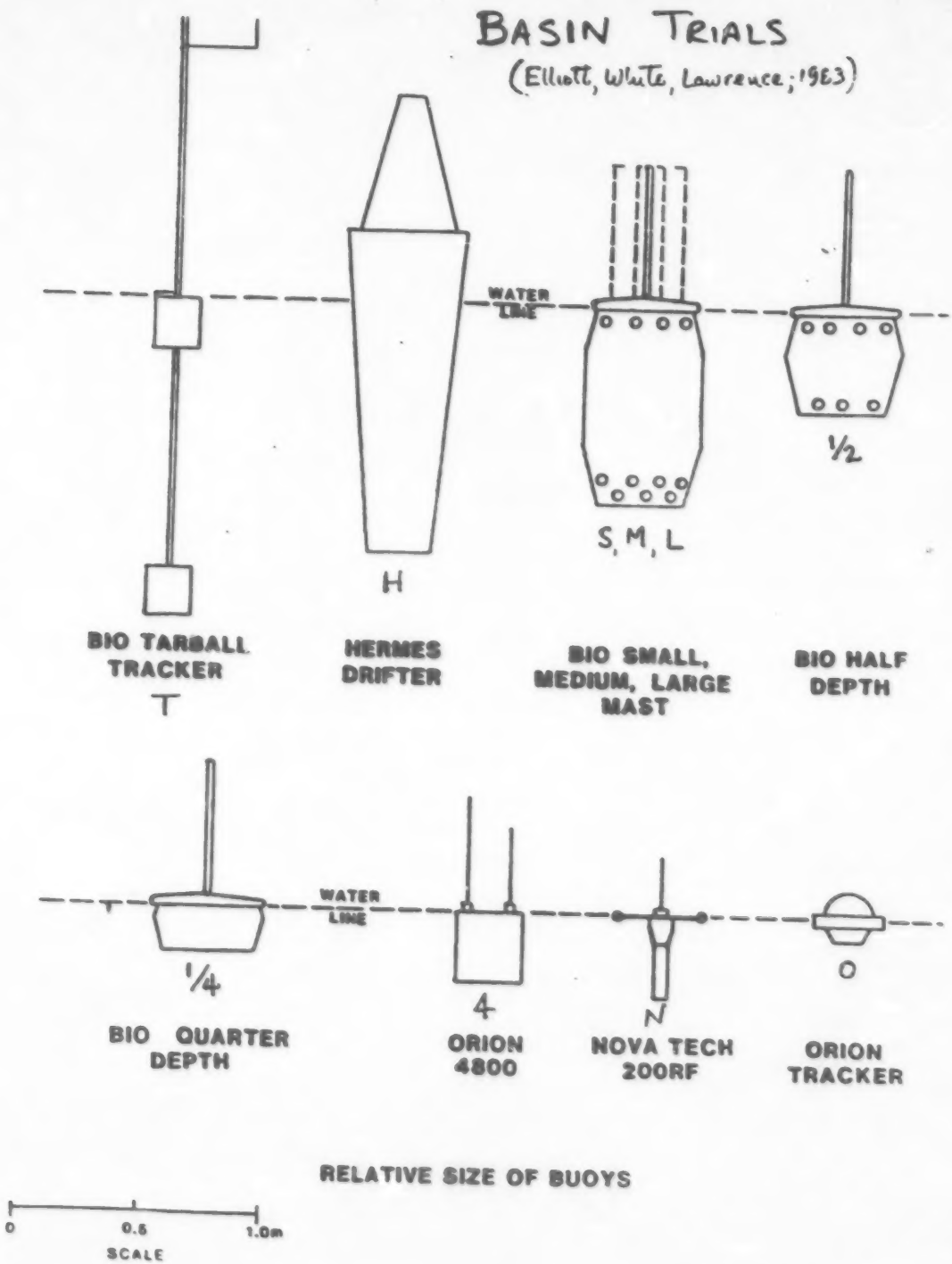


Figure 1. Diagram (to scale) of the entire complement of experimental and commercial buoys used in the Bedford Basin trials. BIO small-(S), medium-(M), and large-(L) masted and half-(1/2) and quarter-(1/4) depth buoys are those to be tested for wind and current shear loading.

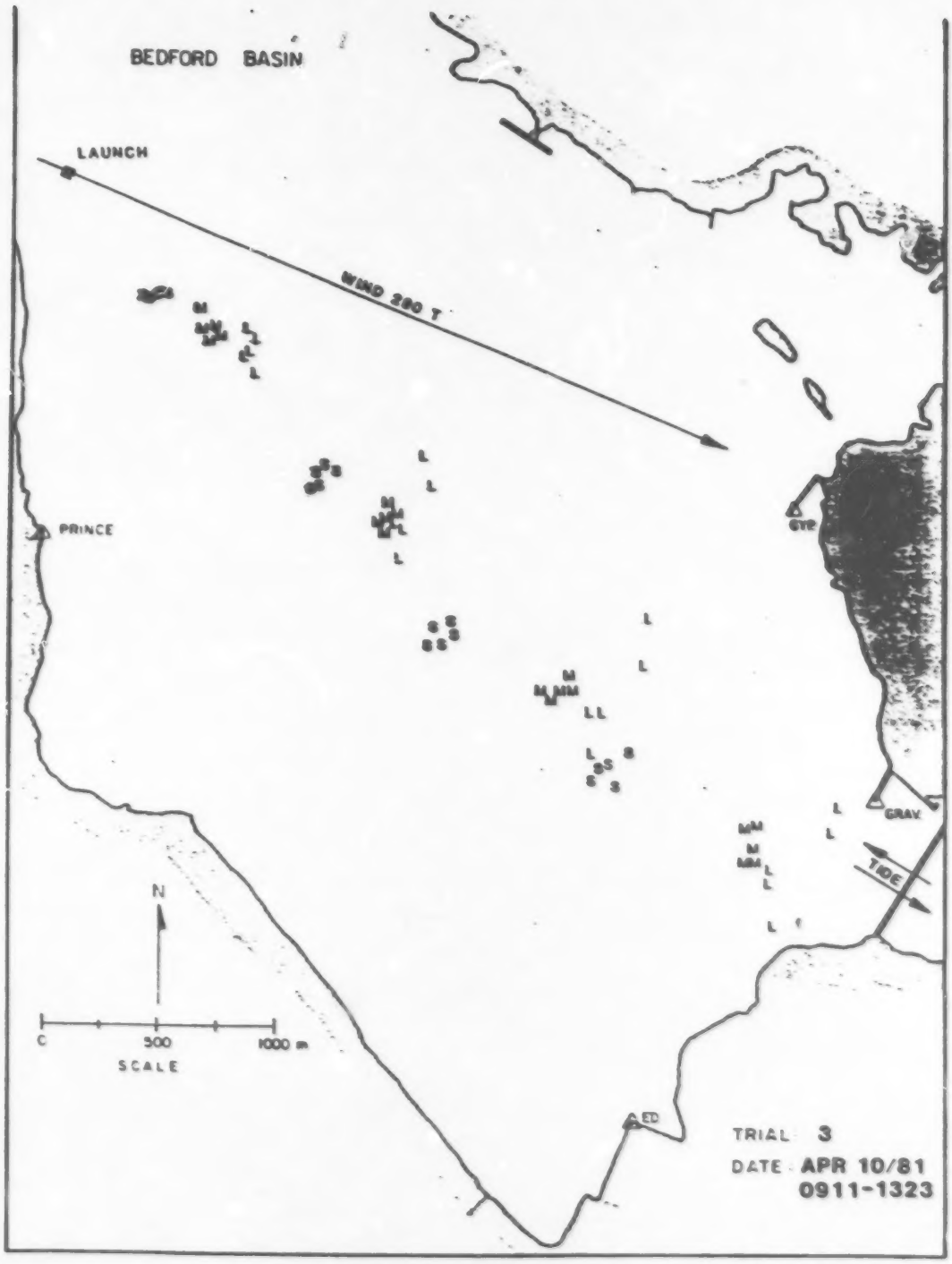
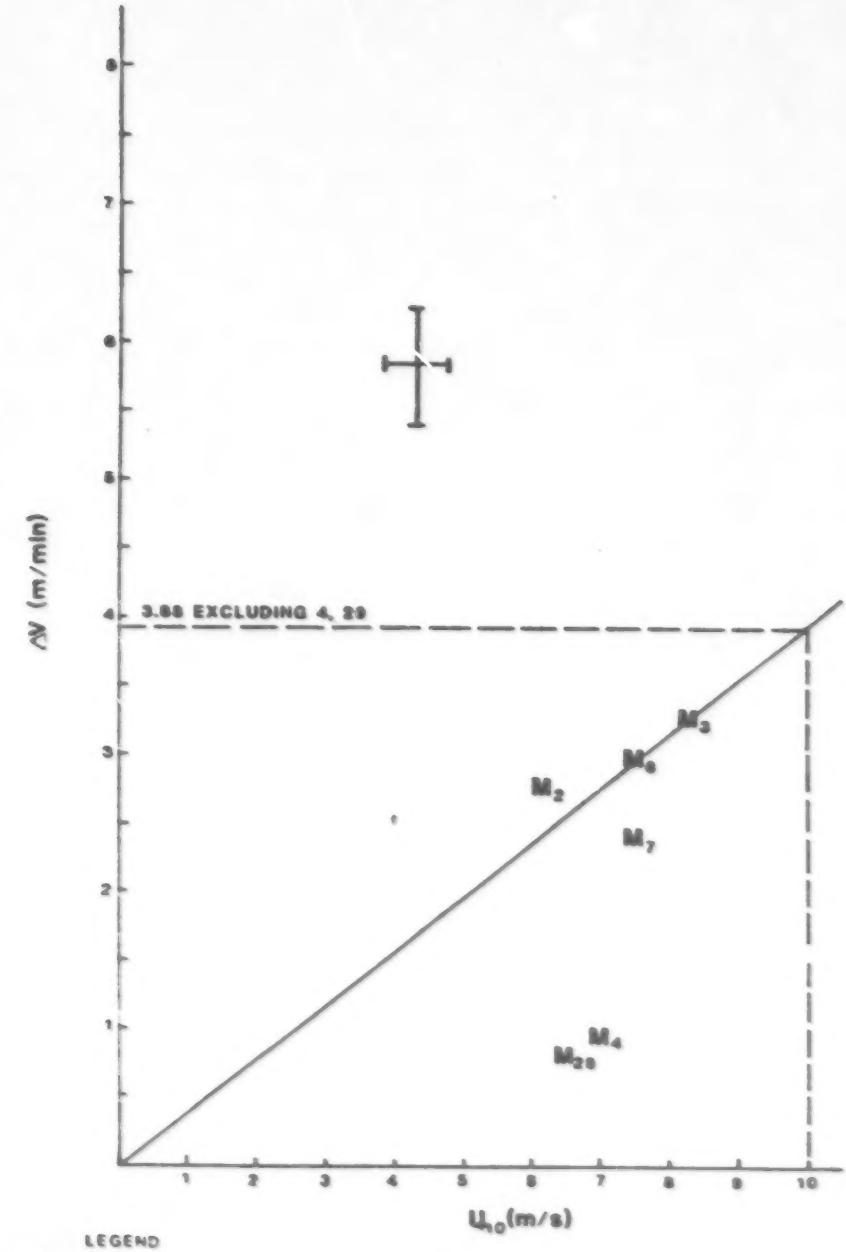


Figure 2. Successive downwind positions of clusters of BIO experimental buoys during Basin trial #3, April 10, 1981. Buoy positioning was accomplished by microwave navigation with respect to sites indicated by open triangles.



RELATIVE BUOY SPEED
(W.R.T. REF. BUOY) Vs WIND SPEED

Figure 3a. Relative buoy speed for 10 kg medium-masted buoys relative to standard (S) as a function of 10 m wind speed. Linear regression is used to project the results out to 10 m s^{-1}. Trials 4 and 29 are excluded because the former involved the first use of aerial photography and is suspect, while the latter was conducted offshore.

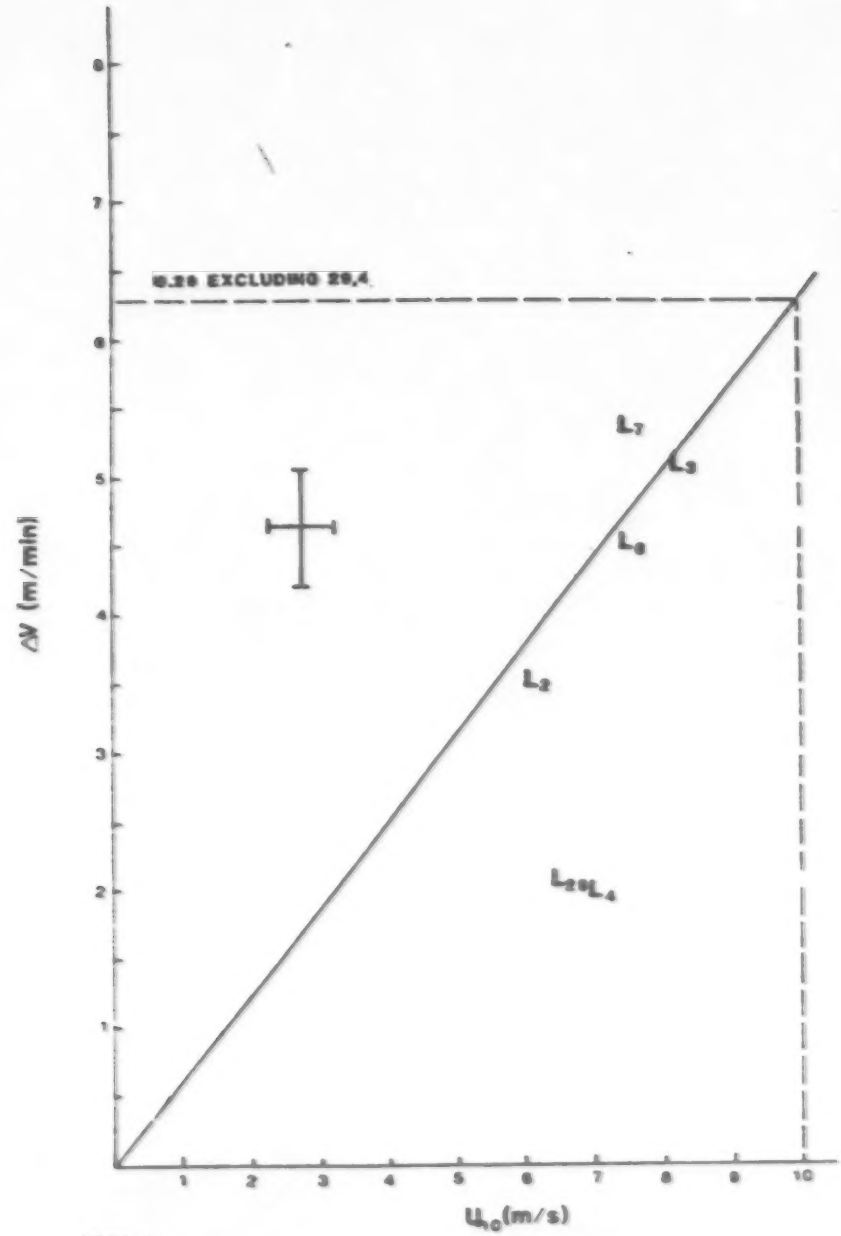


Figure 3b. As in (a) for the large-masted buoys.

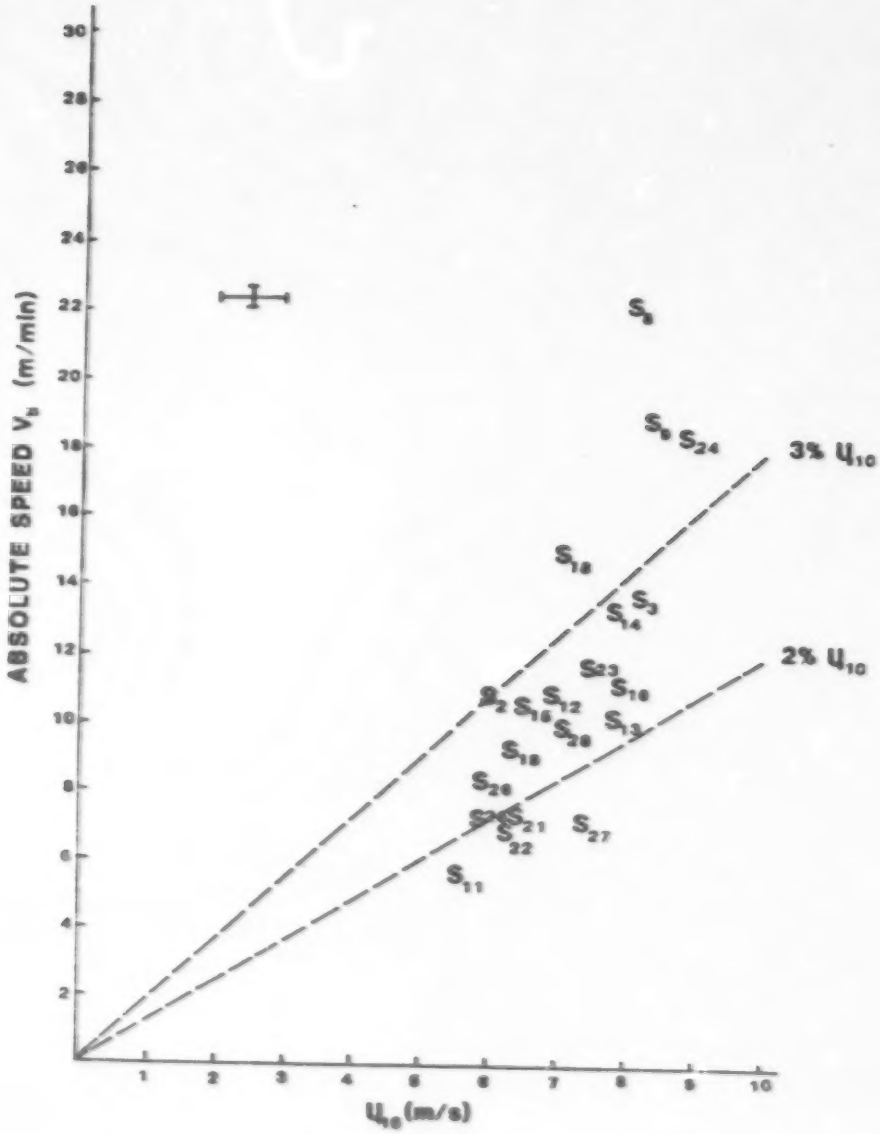


Figure 4. The absolute speed of all standard buoys from all the Basin trials versus the 10 m wind speed.

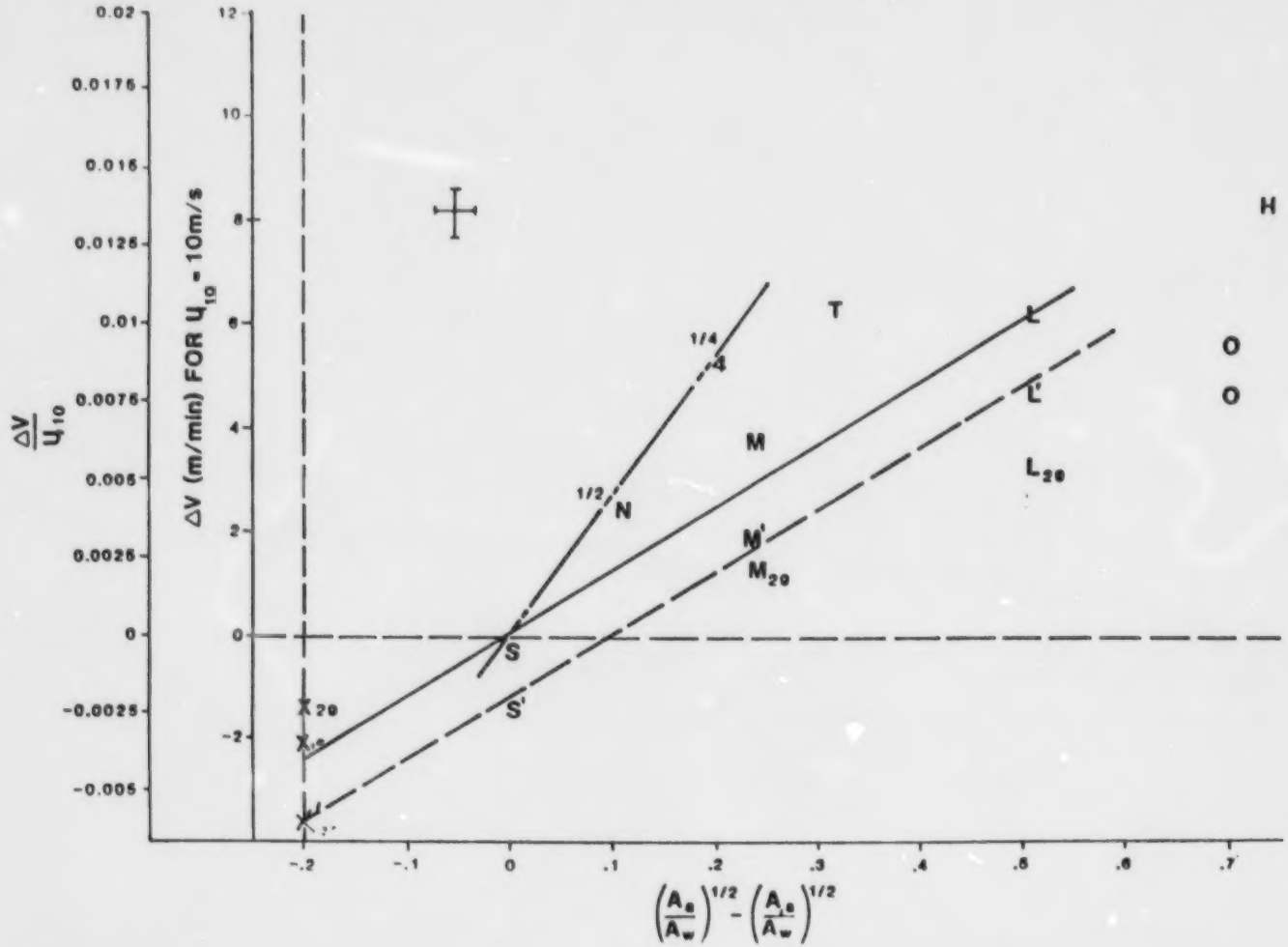


Figure 5. Relative drift of various BIO experimental and commercial buoys with respect to the standard 10 kg, small-masted buoy (S) plotted against the difference of the square roots of the ratios of frontal area above and below the water line. Vertical axes give the speed in m/min for a wind of 10 m s and the relative speed scaled by the wind. Wind loading curves for the 10 kg (X,S,M,L) and 20 kg (X',S',M',L') ballasted buoys are offset. (S,1/2,1/4) is the current shear loading curve. Commercial buoy results (N,O,H,4) are scattered. Results from the single offshore trial (#29) are singular and plotted separately.

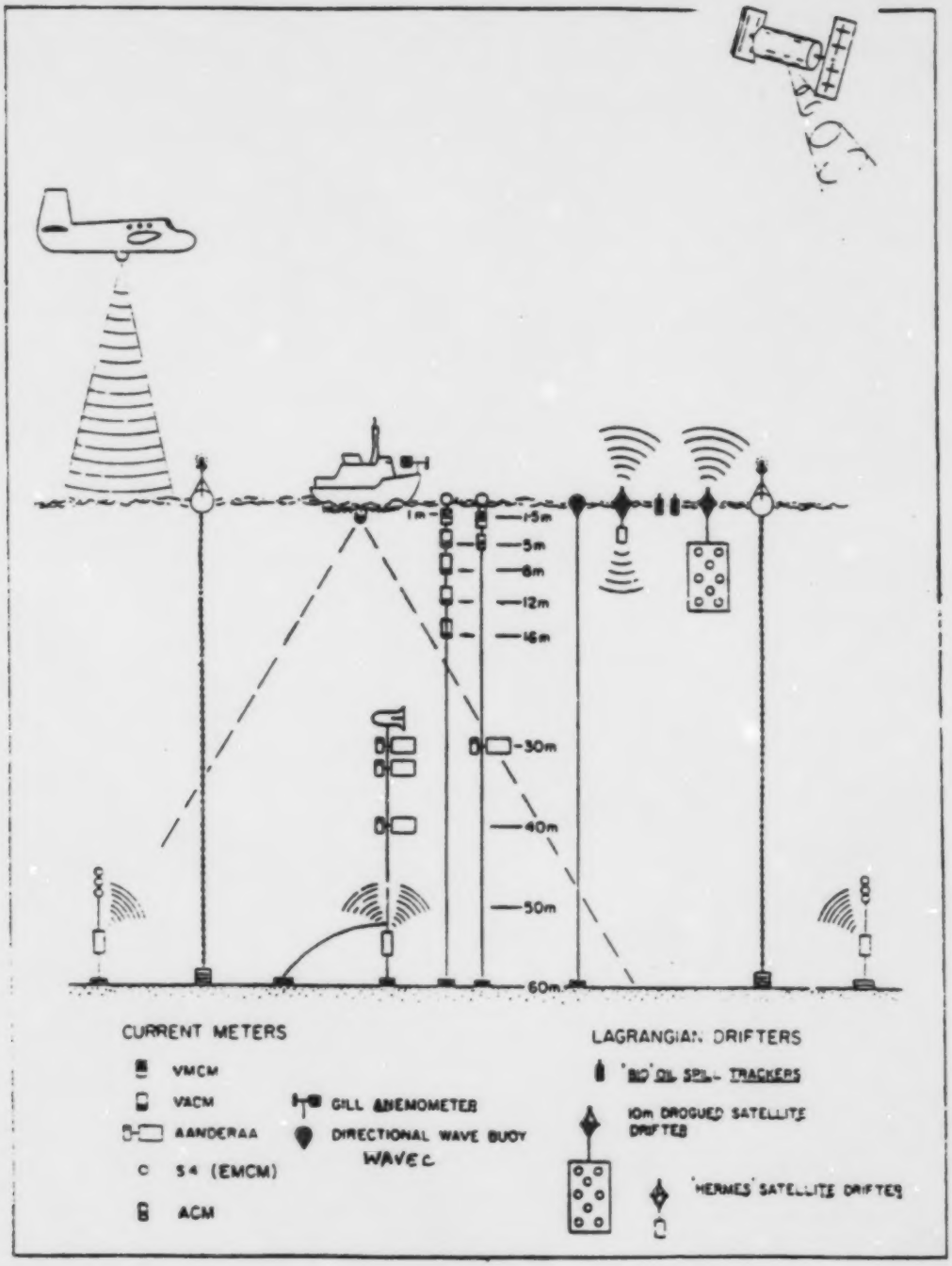


Figure 6. Summary of measurement programs surrounding the Cape Sable trials, including moored current meters, shipborne Doppler profiling and tracking of Lagrangian drifters by satellite, aerial photography and bottom-mounted acoustic transponders.

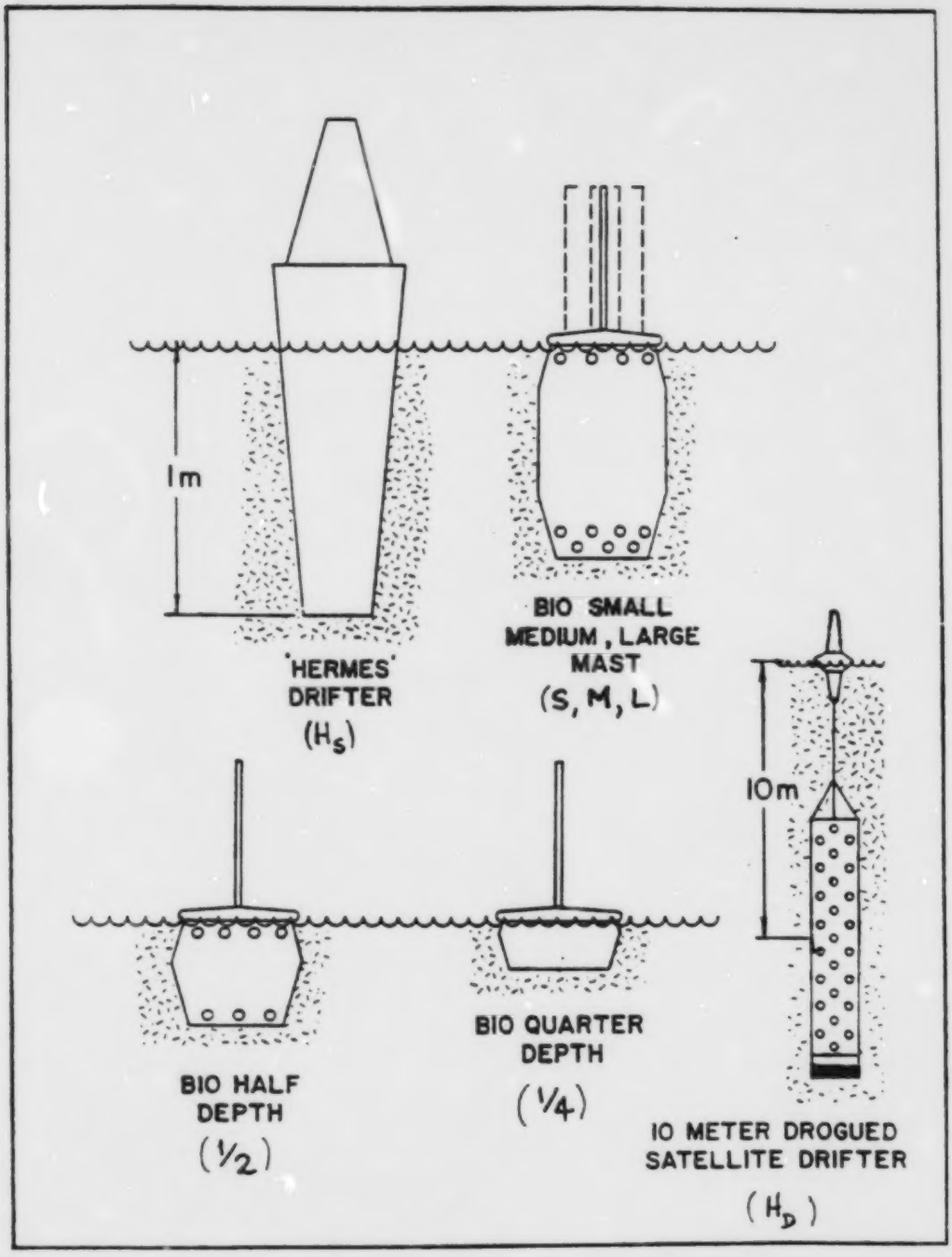


Figure 7. Diagram (to scale) of experimental and commercial drifters used in the Cape Sable trials. (see Fig. 1).

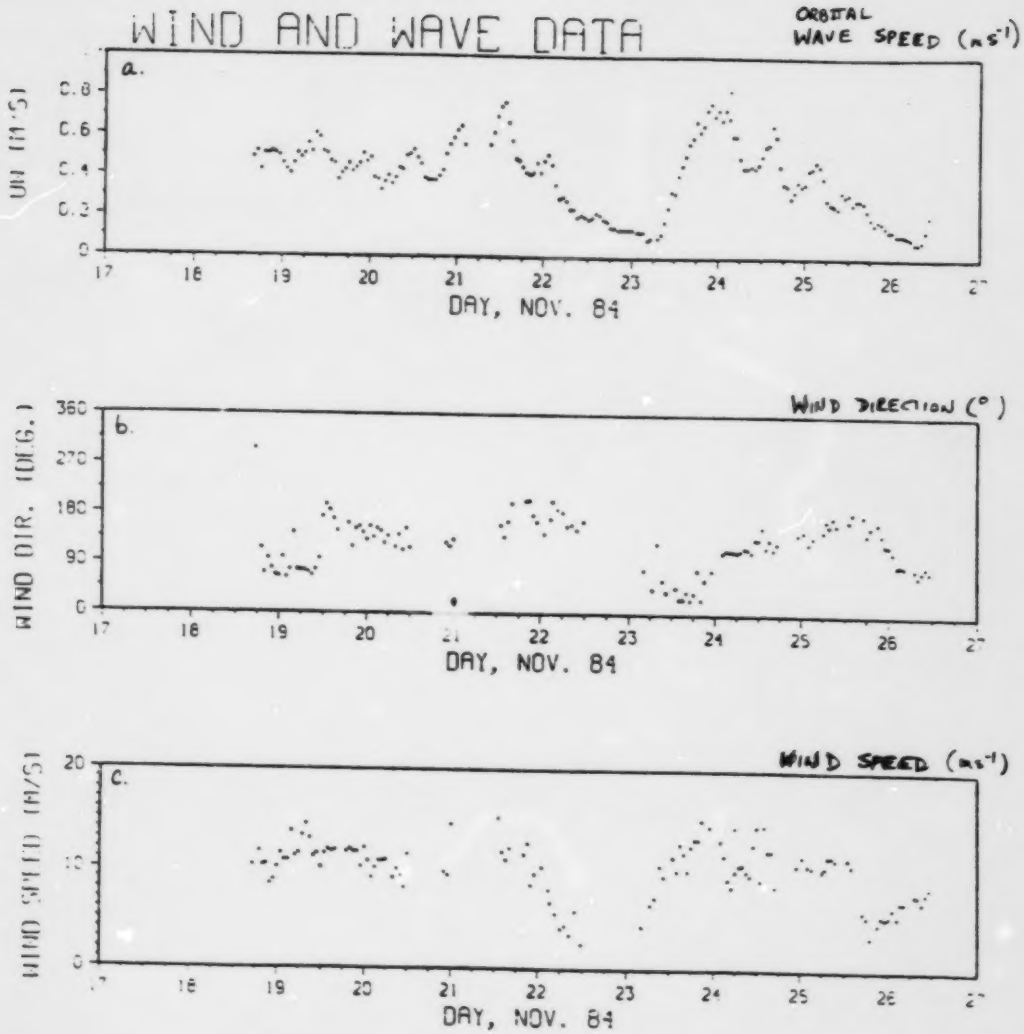


Figure 8. Wind and wave characteristics during the Cape Sable drifter trials, 17-27 November, 1984. (a) Surface wave orbital wave speed, computed by integrating (frequency) *heave spectrum, (b) direction towards which the wind is blowing, (c) wind speed adjusted to 10 m level.

PLOT OF BUOY POSITIONS
FROM CAPE SABLE AERIAL PHOTOGRAPHS

FROM PHOTO # 7
DATE NOV 18 1984, 1853 GMT

Figure 9. Sample distribution of buoys during Cape Sable trial #2, 18 November, 1984. Local wind direction is defined by the orientation of the ship, C.S.S. Dawson.

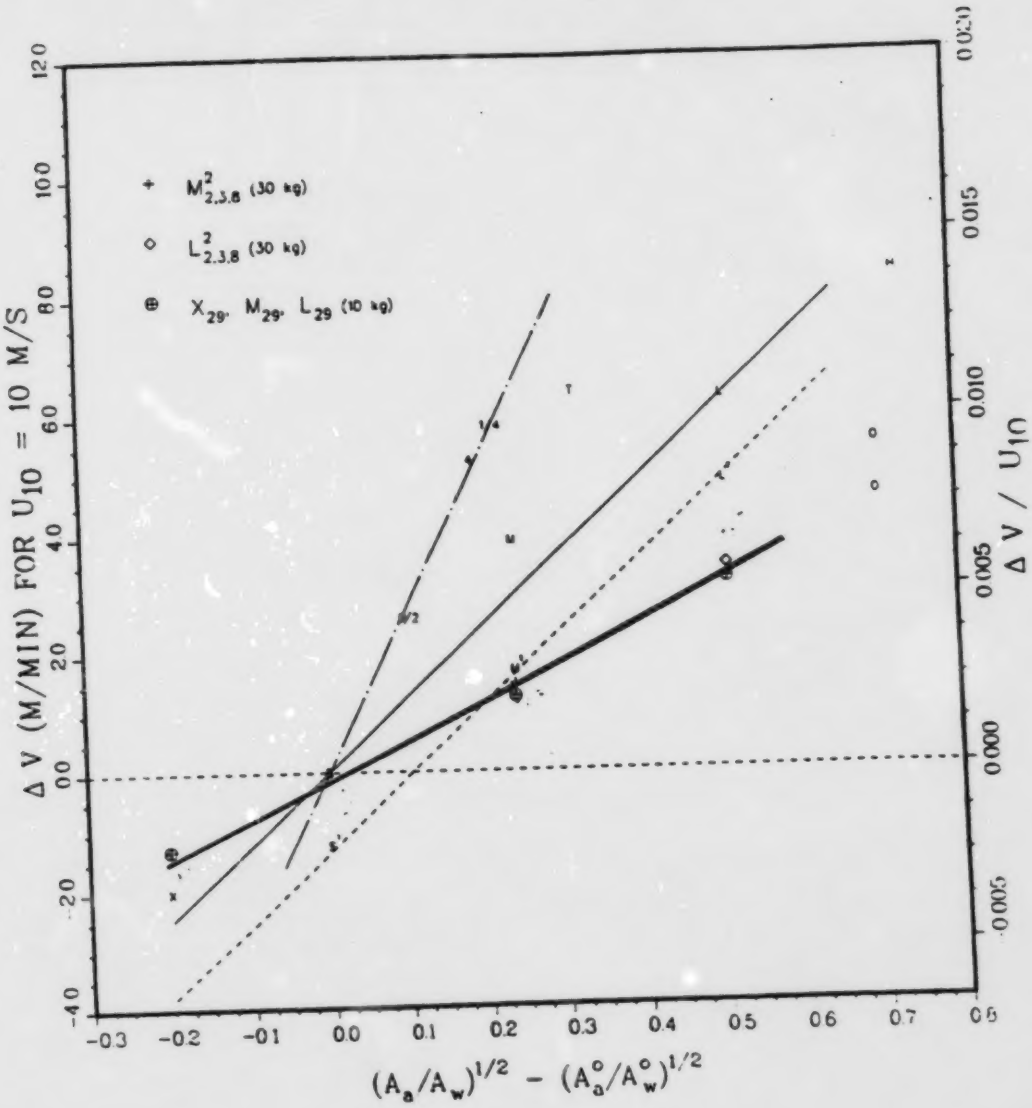


Figure 10. Summary comparison of relative drift measured during the offshore trials off Cape Sable (M ,L ; trials 2,3,8) and Halifax Harbour (trial #29) against the Bedford Basin results. Offshore wind loading curve (thick, solid) is shallower than either the 10-kg (thin, solid), 20-kg (thin, dashed) or current loading (dot-dash) curve from the Basin trials.

VALIDATION DATA BASES

(Abstract Only)

R. Clark
Marine Spill Response Corporation
Washington, DC

A goal was set at the first planning meeting for the Oil Spill Trajectory Model segment of this workshop that has not yet been met. Our original goal was to run several spill models, evaluate their similarities, and to report to you on our findings today. This goal was not met. Today I want to discuss with you why this goal was not met and to solicit your input and help in accomplishing this goal for 1992.

During the summer months of 1991, a trajectory modelling study group was initiated and the following membership was obtained:

Dr. Andrew Vastano - Texas A&M University

Dr. H. Murat Cekirge - A.D. Little

Dr. Peter Smith - Bedford Institute of Oceanography

Mr. Ivan Lissauer - U.S. Coast Guard R&D Center

Dr. Jerry Galt - U.S. National Oceanic and Atmospheric Agency

Mr. Merve Fingas - Environment Canada

Mr. Bob LaBelle - U.S. Department of the Interior

Dr. S. Venkatesh - Atmospheric Environment Service, Canada

The members of this group exchanged ideas and suggestions by phone and fax for several weeks. By September it was clear to me that a trajectory model comparison could not be done in 1991. The concerns raised by each study group member were generally different, but the majority of the members agreed that we should not try to conduct an oil spill model comparison at this time. The most significant reasons given for not conducting a model comparison in 1991 are as follows:

1. There is a lack of ground truthed data to be used in a model comparison.

2. Oil spill models are a tool for the spill trajectory advisor to use in assessing oil movement. These models are not "expert systems" that can be used to automatically project an oil trajectory movement.

3. Several scenarios are needed to test general purpose models under different conditions such as shallow and deep water environments.

4. The adjustments made to compensate for floater movement may add significant error to a model's projection capability.

5. Details of local hydrodynamics are needed before models can predict oil spill projections.

6. An extended period of time is required to prepare the data needed to address the issues in items 1 through 5 above.

As part of our discussions, the membership defined the requirements for a valid design of an oil spill trajectory model comparison experiment. The following components of the design of the experiment is what I want to discuss with you today:

1. Define the User
2. Define the User's Needs
3. Model Requirements to Satisfy User Needs
4. Set Objectives for the Experiment
5. Identify and Obtain Field Data
6. Identify Professional Evaluation Referees
7. Select Trajectory Models for the Experiment
8. Invite Modellers to Participate
9. Complete the Experiment Design
10. Execute Experiment
11. Evaluate the Experiment
12. Report Findings and Publish
13. Assess Effectiveness of Experiment.

After you hear my suggestions for an oil spill trajectory model experiment, I would like to have your input and your future support in completing this experiment.

SUMMARY
APPLIED USES, NEEDS AND ISSUES CONCERNING OIL SPILL TRAJECTORY MODELS

Charles P. Giammona, F. Rainer Engelhardt
Marine Spill Response Corporation
Washington, DC

James Osborne
Environment Canada
Hull, PQ

It is an operational expectation in oil spill response programs that oil spill models and related research can enhance the effectiveness of oil spill countermeasure efforts, especially in the initial hours and days of the spill. The Panel on Energy & Research Development of Canada recognized a need to review the direction of research efforts required to provide effective wave, current, and oil spill trajectory models for operational use. The results of their recent study (Godon, et al 1991) indicate that there is a gap in technology transfer between oil spill researchers and model developers, and oil spill responders as users of advanced oil spill clean up technology. The purpose of the workshop session was to better identify user needs and research priorities associated with operational oil spill models.

CHARACTERISTICS OF AN OIL SPILL MODEL

In the "new age" of oil spill clean up requirements and capabilities, there is a philosophy to collaborate and share in the research and development needed to improve oil spill response. Research and development that would aid operational cleanup measures at the time of an oil spill include a spill trajectory model which: 1) produces accurate results; 2) is applicable to a range of environments and conditions; 3) is cost effective to use; 4) can provide information to the user that is graphic, easy to interpret, and relevant; 5) can provide information quickly; and 6) is easy to use.

It is important to recognize there can be a difference between models used by oil spill responders, contingency planners, or by risk/damage assessors. The use of models for environmental risk assessment may be even more challenging to develop correctly than modelling the trajectory of oil spills in real time.

NEW DIRECTIONS FOR MODELLING EFFORTS

It is the current opinion of many modellers that it is more important to improve data acquisition for models than to improve models or model types. However, the best available technology should be used to increase the effectiveness of predicting an initial spill trajectory and its long term fate. State of the art models coupled with parallel processing technology can help increase the accuracy, speed and effectiveness of clean up strategies beyond existing levels. Such model development should be encouraged.

Predictions of oil spill trajectories are now based on flow fields calculated by historic mean currents and time-dependent wind drift. The potential for inaccurate predictions is high because the actual environmental circulation features during an oil spill event rarely correspond to the flow regimes produced by mathematical averaging of historic data. Mean flow fields in the Gulf of Mexico, Mid-Atlantic Bight and California Current have been compared with actual satellite-derived,

advective flow fields (Vastano, 1985). The increased reliability of trajectory predictions based on remote sensing analyses serve to illustrate that models initialized with near real time submesoscale data can produce very accurate trajectory results. Remote sensing offers the greatest opportunity to improve the data input on the initializing conditions needed for a model. Remote sensing data also generates information about oceanographic phenomena such as convergence zone locations, which can pinpoint discontinuities in the oil slick and thus directly aid the effectiveness of oil spill clean-up operations.

There is some interest in using adjoint models as a way of assimilating data to initialize models. Generic data assimilation techniques developed for other application such as operational fisheries models, may help provide estimates of initial boundary conditions for local or regional models in the future, especially in combination with remote sensing developments.

It is clear even after 20 years of oil spill model development, that model users and model makers still differ in their perception of the usefulness of model output. In part, this is because what is needed in a model depends upon what the model will be used for - and those requirements vary technically, operationally, legally, and politically. There is, however, more agreement that: 1) work is needed on algorithms that better predict oil fate; 2) quality environmental information is needed to drive models to more accurate results; and 3) tailoring models to regional scales is important for improved model accuracy.

VERIFYING MODEL RESULTS

The reliability and sensitivity of oil spill model results can be verified by evaluating individual model parameters, i.e., particular assumptions can be compared with actual oil spill trajectories and other appropriate observations. Simple "hindcasts" are often used to better understand some of the bias within models, but statistically verifying the results is still difficult.

Experimental spills, or accidental "spills of opportunity" that are used in oil spill research programs, do not always effectively help in comparing model predictions with observations from real spills. It may be possible to test the sensitivity of models by using surface drifters to simulate the drift and horizontal dispersion of oil in lieu of using real oil. The effectiveness of such an approach is relatively unknown because of the difficulties in "calibrating" drifters so they reflect true oil drift.

Other ways to evaluate operational models focus on comparative testing using the same environmental and oil properties data sets in order to better understand what it is that models have in common and what it is they can do reasonably well. However, there is little support from modellers to have their models operationally compared with each other. Reluctance for comparative testing is primarily based on: 1) the uncertainty of test input parameters; 2) the notion that model output is also based on the "expertise" of the modeller and other "experience factors" derived at a spill site during a spill; and 3) concern about over interpretation of the final results, relative to the design capability of the model.

OTHER CONSIDERATIONS IN PREDICTING AN OIL SPILL TRAJECTORY

Finally, numerical models are not the only factor used in predicting oil spill trajectories any more than economic models are solely used to direct financial decisions within a corporation. It must be recognized that models are part of an interactive, oil spill technical response system that includes the model, the model expert, and other experience and environmental factors. Improvements to that system would include: 1) more comprehensive data input; 2) better quality databases; 3) better recognition in the importance of key operational personnel and the

"international oil spill knowledge base" in the interpretation of model output; 4) better documentation of the systems approach used in a technical response to an oil spill; and 5) effective linkages within the regional or local emergency response community.

Ongoing linkages between model developers and users within government, industry, and academia are especially necessary to understand and integrate: 1) the complex technical environmental dynamics; and 2) the non-quantifiable issues associated with accidental oil spills. A committee comprised of interested parties (producers and consumers of spill models) should meet on a periodic basis to consult and review priorities, assuring that oil spill tracking model development proceeds at a pace and in a direction relevant to bother regulators and responders.

An outline of oil spill trajectory model uses, needs and issues can be summarized as follows:

I. Purpose of oil spill trajectory modelling

A. Most efficient deployment of resources for containment, protection and clean-up
B. Risk assessment and contingency planning
C. Training

II. Use of trajectory models

A. Preparedness
- Response Training
- Risk Assessment
- Contingency Planning

B. Response
- Equipment Deployment
- Closure to Traffic
- Monitoring

C. Post-Spill
- Damage claims
- Evaluate effectiveness of contingency plan - QA
- Anticipatory environmental monitoring for effects

III. Primary Research Needs

A. System Approach

B. Behavioral Model
- real time data integration
- fate algorithms
- ocean currents data
- wind field data
- useful output for the user

IV. User Needs

A. Model Characteristics
- accuracy
- user-friendly/relevant
- risk determinations
- understandable output
- real time model
- decision support

V. Other Research Needs

A. Emulsification factors
B. Model verification
C. Data set verification
D. Linking fate and trajectories
E. Develop dynamic based upper ocean numerical models
F. Measure oil spill thickness
G. Vertical dispersion and horizontal spreading
H. Subsurface prediction
I. Chemical and oil spills
J. Geographic area
K. Spill properties
L. Algorithms not physically based
M. Geographic Information System (GIS) compatibility
N. Better fate algorithms
O. 3D model development
P. Improve existing rather than developing new systems (200 models presently exist)
Q. Models for oil in ice

POSTER PRESENTATIONS

A STATE-OF-THE-ART OIL SPILL MODEL SYSTEM FOR RESPONSE AND CONTINGENCY PLANNING

Mark Reed and Malcolm L. Spaulding
Applied Science Associates, Inc.

A consortium of private and public organizations was formed to develop a state-of-the-art oil spill model system for oil spill response and contingency planning. The consortium behind the new system consists of Exxon, Chevron, Mobil, the Canadian Petroleum Association, Environment Canada, the U.S. Army Corps of Engineers, and ASA.

The model system enables the user to predict the trajectory of an oil spill anywhere on the globe. Within 30 minutes of a spill, the user is able to investigate a variety of oil spill scenarios including alternate weather forecasts and response strategies. The model also has the capability to be updated based on remotely sensed observations of the oil distribution and composition.

The model has been developed for operation on the latest generation of personal and lap-top computers. Deterministic and stochastic spill forecasts for spill sites throughout the world are available at low environmental data resolution (~1 km), or in selected areas using high resolution data. The system features rapid setup and response times, and alternate procedures to specify environmental data (digitization, "painting" using a mouse and graphical interface, keyboard entry, and direct electronic links). Modules are also provided to interface with other oil spill support computer systems and private/government data bases. Menus, mouse- or keyboard-controlled operation, graphics and animations are used extensively for data input/output and visualization of model results.

The oil spill fates model allows the user to select from a variety of algorithms to predict drifting, spreading, evaporation, emulsification, entrainment, dissolution, sedimentation, decay, shoreline interactions, and ice-oil interactions for a user-selectable oil type. The model predicts the oil distribution (trajectories) and fate (mass balance) as a function of time for instantaneous or continuous spills from single or multiple, surface or subsurface sources.

Environmental data are user-selectable and include the ability to use constant, time series, spatially varying time series, or statistically generated time series data. The project is scheduled for completion in January of 1993.

An Operational Integrated Sea Ice and Iceberg Forecast System (IIFS)

Mona El-Tahan, M.Eng., P.Eng.

C-CORE
Centre for Cold Ocean Resources Engineering
Memorial University of Newfoundland
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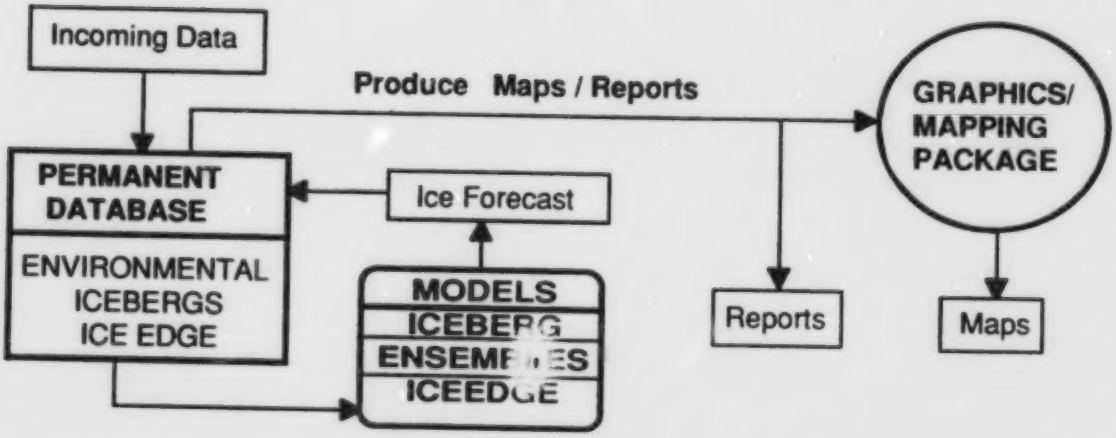

COREtec, in conjunction with its parent organization the Centre for Cold Ocean Resources Engineering (C-CORE), has developed an operational integrated Sea Ice and Iceberg Forecasting and Data Management System (IIFS). The IIFS is an integrated computer software that has many unique features designed to meet the needs of ice management in the offshore industry. The IIFS is based on the state-of-the-art technology that has been used by both industrial and government clients.

The IIFS includes three operationally used and verified ice forecasting models for the prediction of Sea Ice Edge Drift, Iceberg Drift Trajectory and Iceberg Ensembles Drift. The IIFS system also includes a comprehensive database on icebergs and powerful graphics component. The database contains information on icebergs (size parameters, drift trajectories, drift speed, densities, flux), ice edges, wind and currents. The graphics component utilizes an electronic mapping program for the display of observed and forecasted position of icebergs and sea ice edges, currents and wind vectors, bathymetry and coast lines, ship and rig locations, and flight routes.

The forecast models are designed to utilize forecasted, measured, statistical and/or deduced environmental conditions as well as iceberg parameters to provide forecasts of ice and iceberg drift for periods up to 48 hours. The models account for temporal and spatial variations in the wind and water currents and provide confidence factors associated with the forecast based on uncertainties in wind and current information.

PERD Ocean Model Workshop
Halifax, Nova Scotia, Canada
15-17 January 1992

The Spill Analysis Workstation (SAW)

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ABSTRACT

A number of large oil spills in recent years has attracted ambient environmental concern and re-focused public attention on the ability to limit the risks associated with production and transportation of hydrocarbons and other chemicals and on the ability to respond efficiently to spills. This paper (poster) presents a spill emergency management system developed at the Danish Hydraulic Institute in cooperation with a sister organization, the Water Quality Institute. A user-friendly, map-based menu system guides the relatively unexperienced user through use of the model tool. Recent spill responses have showed that simplicity of the model end-user-interface is crucial in avoiding stress related mistakes during response planning.

1. INTRODUCTION

The SPILL ANALYSIS WORKSTATION (SAW) is a software package for use in spill response operations related to oil spills as well as spills of other chemical substances into coastal waters or seas. SAW gives answers to critical questions such as:

- Where will a spilt substance most likely move within the next hours or days?
- How large an area is likely to be affected?
- What concentrations can be expected at specific locations?

SAW provides those answers within minutes, saving valuable time during those crucial initial hours or minutes when the success of the spill response is very often determined. SAW is operated through a very advanced graphical user interface (GUI) which includes crisp, on-line 2-D and 3-D colour animation of simulation results.

SAW is an OPEN software package. It is easy to use SAW together with software from other vendors, e.g. data base systems or

expert systems. SAW is available for UNIX (HP-UX, ULTRIX, SCO UNIX and more) and VAX VMS running X-Window and Motif.

2. APPLICATIONS

SAW contains advanced numerical modules for simulation of the physical, chemical, and biological processes which are of importance for a wide range of possible spill scenarios. Fig. 2.1 shows the main spill types or "pathways" covered by SAW.

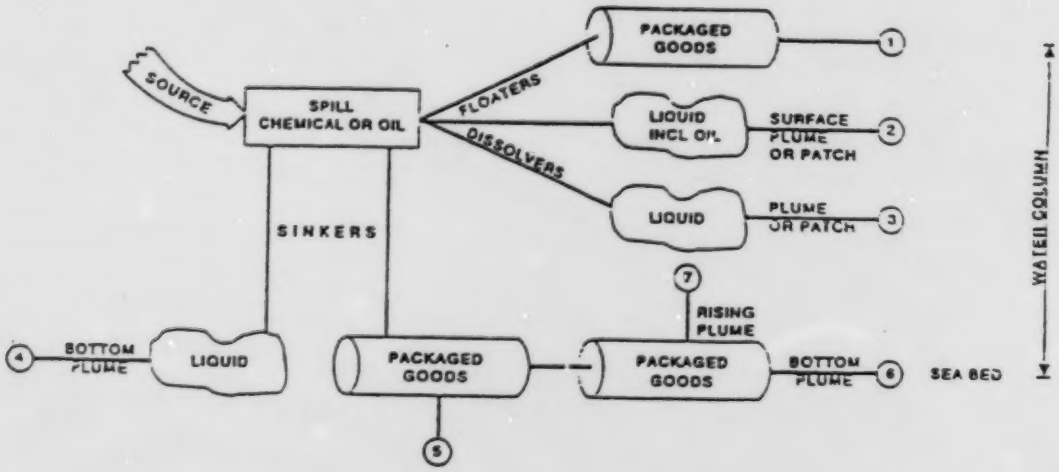

Fig. 2.1 Spill Pathways.

The figure reflects the nature of the spilled matter being floaters, dissolvers or sinkers. The spill can be as packaged goods (drums etc.) or as free chemicals (liquid or solid). Depending on the nature of the chemical, the spillage will float (drums, oil and other low density and low solubility chemicals), be dissolved (soluble chemicals) or sink (drums and high density, low solubility chemicals).

The SAW model is capable of describing:

- The drift of floating drums and other objects
- The drift, spreading and weathering of oil
- The drift and spreading of other floating liquids
- The transport and spreading and fate of soluble chemicals in a larger geographical area
- The sinking and spreading of heavy chemicals
- The sinking of drums and other objects

- The drift and spreading of chemicals from broken goods (rising to the surface or staying at the bottom)

3. SAW SIMULATION MODES AND MODULES

3.1 Main Simulation Modes

The Spill Analysis Workstation is applied for simulations of spill scenarios. Such simulations are of relevance in two different connections:

1. In contingency operations, i.e. as a decision support tool during actual spill incidents.

   In this case SAW is applied in forecast mode with forecast meteorological and hydrographical input values.

2. In contingency planning of the response actions to be undertaken for accidents.

   In this case SAW is applied as a simulator in "hindcast" mode, i.e. using typical or historical meteorological and hydrographical input values.

3.2 Wind and Current Input Data

SAW requires certain meteorological and hydrographical input parameters (primarily wind and current values) to be able to compute the track of a spill. These parameters must be specified for each gridpoint in SAW's main computational grid. However, a number of different options are available for fast and easy input of the meteorological and hydrographical data:

- The optimal solution in terms of speed and reliability is to establish a link to a forecast service which can provide the required information.

- Alternatively, hydrographical data can be computed on a local workstation based on input forecast data for wind and air pressure. MIKE 21 HD is the ideal tool for such computations. Adding current forecast computation to the operational procedures typically requires 2 - 10 minutes computing before the SAW is ready for action.

- Finally, wind and current information can be entered directly by the user as time varying, but spatially constant values. This option is of course only recommend-able for areas with relatively constant or low current speeds, e.g. areas far offshore.

3.3 Spill Specific Input data

The main spill specific input data are the position of the spill and the scenario (chosen among the ones mentioned in chapter 2) describing the spill situation. Depending on the chosen scenario or in fact the spill circumstances different kinds of input are needed to simulate the spill. Common to all scenarios are, that the amount of matter e.g. number of drums or mass of substance, and the nature of the spilled matter e.g. size and density of drums or chemical data/fate parameters for chemical substances or composition/nature of oil, have to be given by the user. The spill specific input data for each scenario are shortly touched upon below, one at a time and organized consistently with the figure and the list in chapter 2.

1. **Floating objects**: Number of objects, Dispersion coefficient, Drift coefficient.

2a. **Oil spill**: Composition of the oil (divided into six fractions), type of spill (instantaneous or continuous), Amount of oil (once or per timestep), Drift parameters, Wave parameters, Oil parameters (evaporation rate, vertical and horizontal dispersion rate, etc.)

2b. **Floating liquids**: Rate of discharge, Concentration of chemical in discharge, Dispersion coefficients, Drift coefficients.

3. **Dissolvers** (Far field): Type of spill, Rate of discharge,Concentration of chemical in discharged fluid,Relevant fate processes (choice among several in a list), Parameters and substance properties necessary for modelling the chosen fate processes.

4. **Sinking chemicals** (as a plume): Type of spill, Rate of discharge, Concentration of chemical in discharge, Density of discharged fluid, Ambient density, Dispersion coefficients, Depth of source point.

5. **Sinking Objects**: Number of objects, Size of object, Density of object, Dispersion coefficient (vertically).

6. **Rising or bottom plume**, Identical to the above described for sinking chemicals (plumes). The specified density of the chemical will cause the transport to be upwards or along the bottom.

3.4 Key Simulation Modules

The SAW package contains the following main simulation modules:

Tracking module

The tracking module is used in the simulation of the tracks of the different types of spills. The module reads current speeds and directions (surface, bottom or average over depth values as appropriate for the given scenario) and computes the movements of a particle.

The tracking module can be applied to a single particle ("floating object" or "man over board" scenario), to a large number of particles released simultaneously or to particles released continuously at a specified rate per hour.

The tracking module can take spreading into account through a dispersion coefficient specified by the user.

Advection-Dispersion (AD) module

The AD module computes concentrations of chemicals which are dissolved in the water. The processes covered in the AD module are advection and dispersion. The AD module is applied in the far-field computations for the "dissolvers" scenario.

Spreading and weathering module

This module calculates both spreading and weathering of spilled oil. This oil spill module considers the processes important in spreading and weathering within the first week of the spill:

- Oil slick area growth (i.e. spreading)
- Evaporation
- Dissolution
- Vertical dispersion
- Emulsification
- Upwelling of the dispersed oil droplets

The spreading is assumed to be determined by horizontal dispersion and by a number of forces, set up into force balances for the different oil spreading phases. The important forces are surface tension, gravity, inertia and viscosity friction forces.

A main assumption in the calculation of weathering processes and physical and chemical properties of the oil is a division of the oil into six fractions determined by the boiling point curve and by the alkane and aromate content of the oil. Each fraction is then assumed to have specific properties (density, molecular weight etc.).

The spreading and weathering module consists of a number of submodules, which are interactively coupled as shown in the figure on the next page.

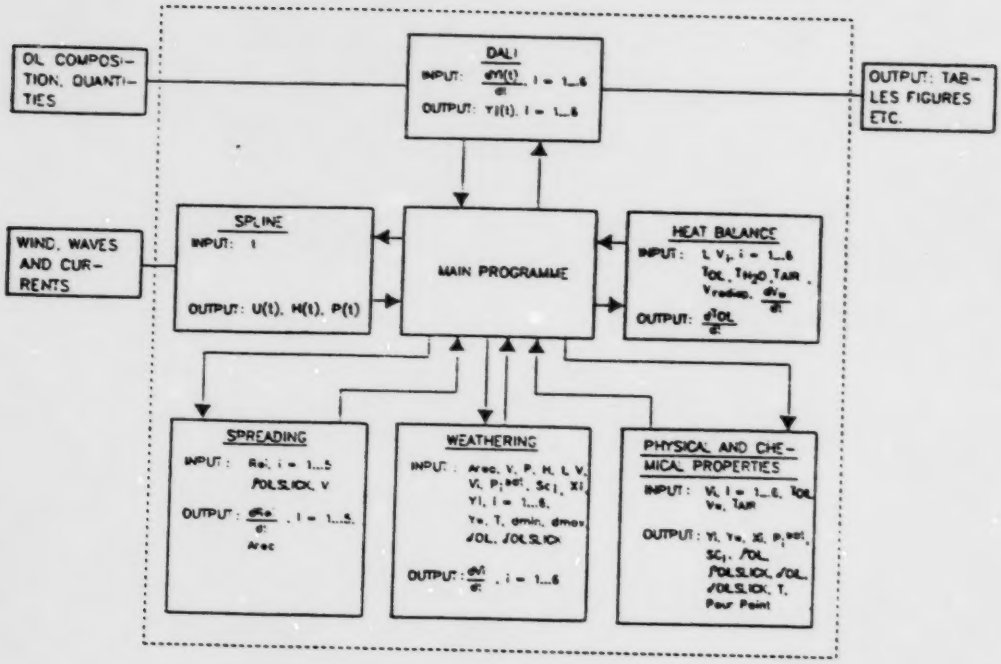

Figure 3.1. The structure of the spreading and weathering module.

The module calculates the slick area growth, the change in oil composition, the density, viscosity, surface tension and oil pour point and the total slick volume, water content and oil content.

Chemical fate module

The FATE module calculates the fate or degradation of chemical substances (other than oil) more or less dissolved in the water column (i.e. not chemicals floating as a slick on the water surface). The fate module considers the following processes :

- Evaporation
- Photolysis
- Chemical oxidation
- Hydrolysis
- Biodegradation
- Adsorption/desorption
- Sedimentation (adsorbed to particulates)

The user will only have to specify data for the processes relevant to the actually spilled chemical. The relevant processes

have to be chosen among the ones listed above. The result of the fate calculation is then the concentrations of total chemical and the concentrations of chemical dissolved in water, adsorbed to suspended matter and accumulated in biota. Only the chemical dissolved in water is bio-available. Chemicals having high affinity to adsorb to suspended matter will by this mean settle along with the suspended matter and be transported out of the water column.

4. WORKING WITH THE SPILL ANALYSIS WORKSTATION

The user interface of the Spill Analysis Workstation has the following main characteristics:

A. **It is window based.** Windows with information are opened and closed during operation, sometimes by the user, sometimes automatically.

B. **It is mouse operated.**

C. **It is MAP oriented.** The key window always contains a digitized map (the "Base Map") of the area of interest. The user can specify input in this window (e.g. specify the location of a spill). Key results are displayed as overlays to the map (e.g. tracks, concentrations, current).

4.1 The Base Map

The Base Map can be configured by the user. An example is shown in Figure 4.1. Several Base Maps may be prepared and the user can select one of these at start-up of SAW.

4.2 Zoom and Pan

The user can zoom in and out and pan to select the most relevant level of detail and sub-area from the Base Map. An "Overview" facility is available. When invoked, a separate window is opened with a small copy of the entire Base Map and a box showing the sub-area which the user has currently zoomed in on.

4.3 Scenario Specification Menu

When the SIMULATION BUTTON is prressed a pull-down menu appears, where the scenario (oil spill, floating drums, etc) can be selected by pointing and clicking in the appropriate fields. This triggers a pop-up menu where the appropriate parameter values corresponding to the requested scenario can be entered, e.g oil discharge. The 'floating liquids' menu is shown as an example is shown in Figure 4.3.

A set of default values are always given in the parameter menu. The user may store in advance a number of relevant combinations of default parameters e.g. "Brent Crude", "HCL", etc. These combinations can then be easily reloaded.

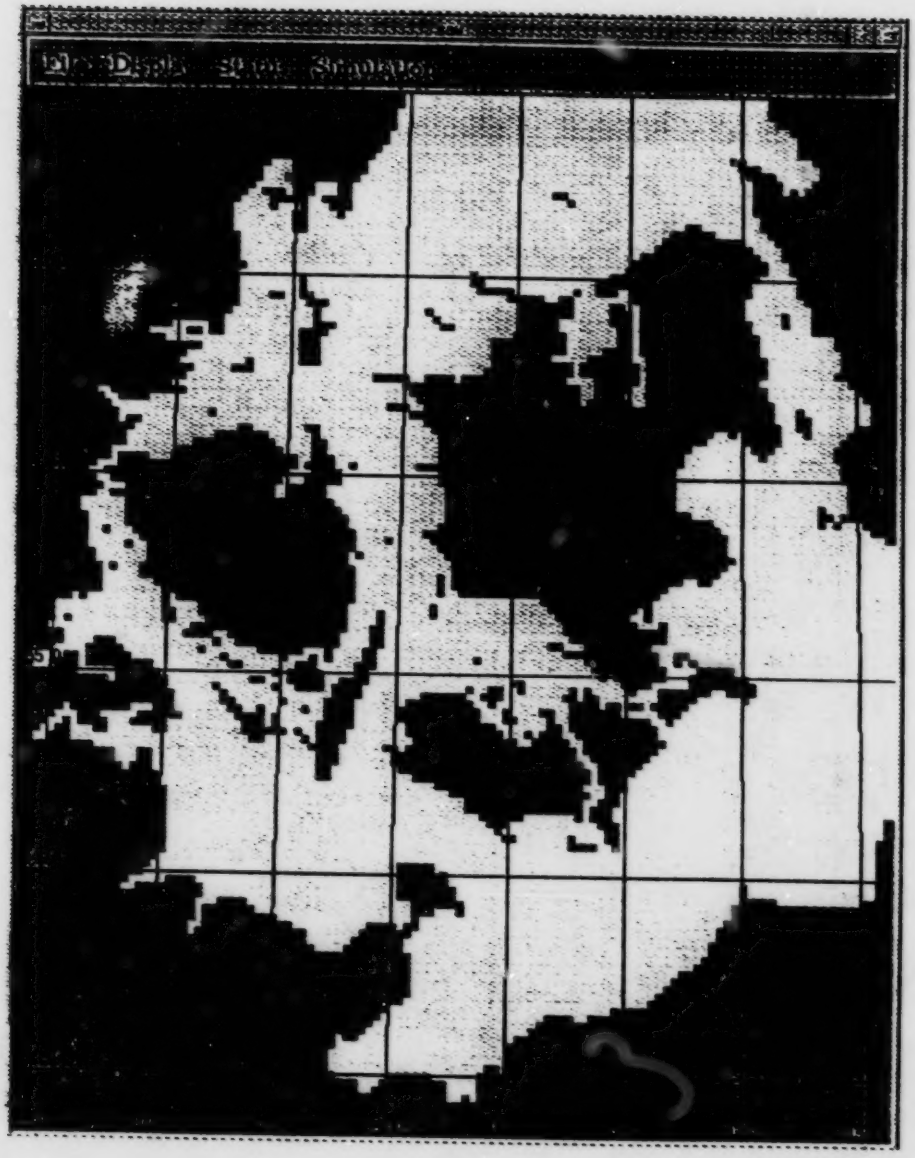

Fig. 4.1 Base Map Example

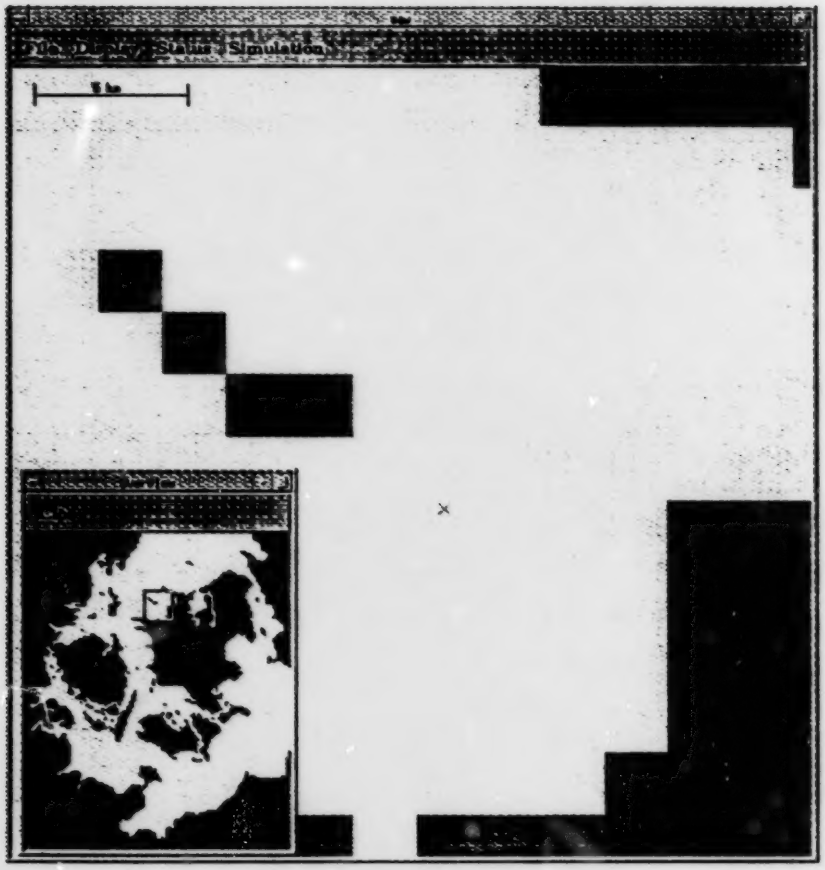

Fig. 4.2 Zoomed Base Map and Overview Window.

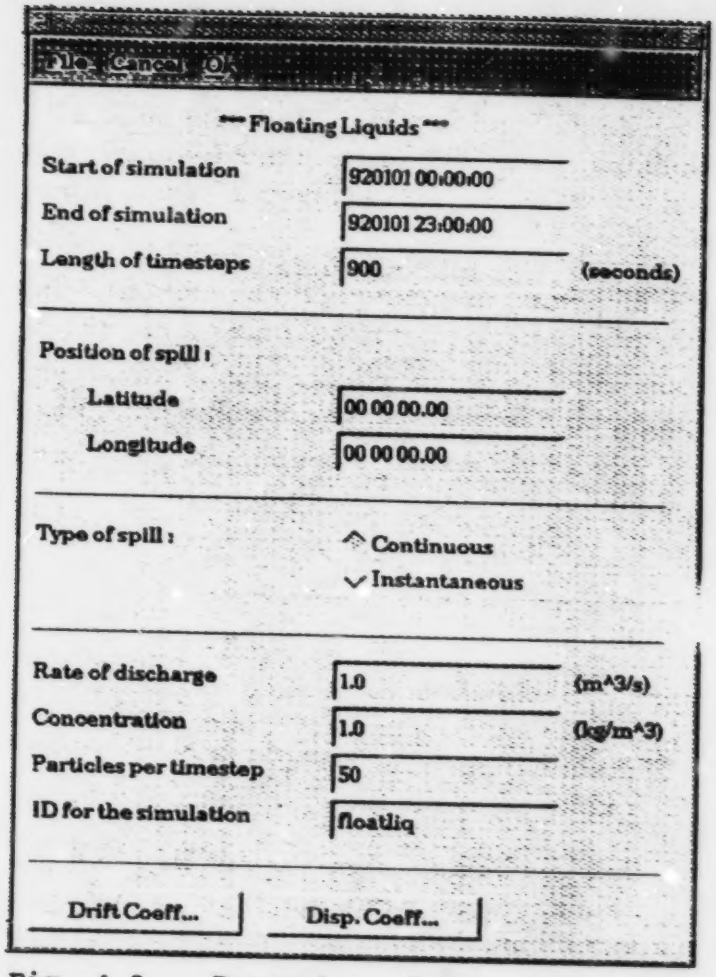

Fig. 4.3 Parameter Input Menu for "Floating Liquid" Scenario.

4.4 Selecting Position of Spill

The spill position is selected by pointing and clicking the mouse on the appropriate position on the Base Map or by entering the coordinates in the parameter menu. In both cases, both displays (x on map and coordinates in menu) will be updated automatically.

4.5 Controlling the Simulation

After completion of all parameter menus, the user presses the OK button. This triggers a pop-up menu for simulation control. The user may run the simulation one time-step at a time (SINGLE STEP) or at the speed of the work-station (START). The simulation results are then shown as overlays on the Base Map together with the input current field, see Figure 4.4.

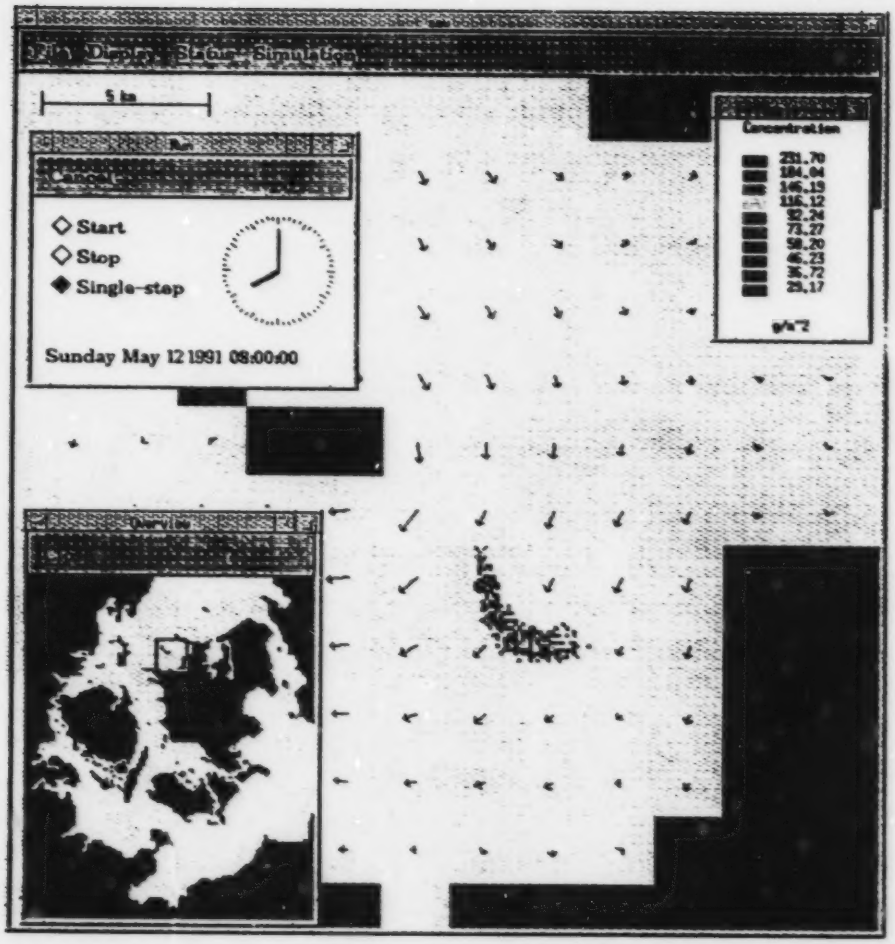

Fig. 4.4 Base Map During a Simulation

4.6 3-D View Facility

The 3-D view facility in the present version of SAW can provide the user with a view of the bathymetry of the simulation area. The 3-D view facility always displays the part of the Base Map which the user has presently zoomed in on. The user may look at the bathymetry from any angle and the horizontal scale can be modified at will. Further display facilities will be incorporated in the 3-D mode in the near future.

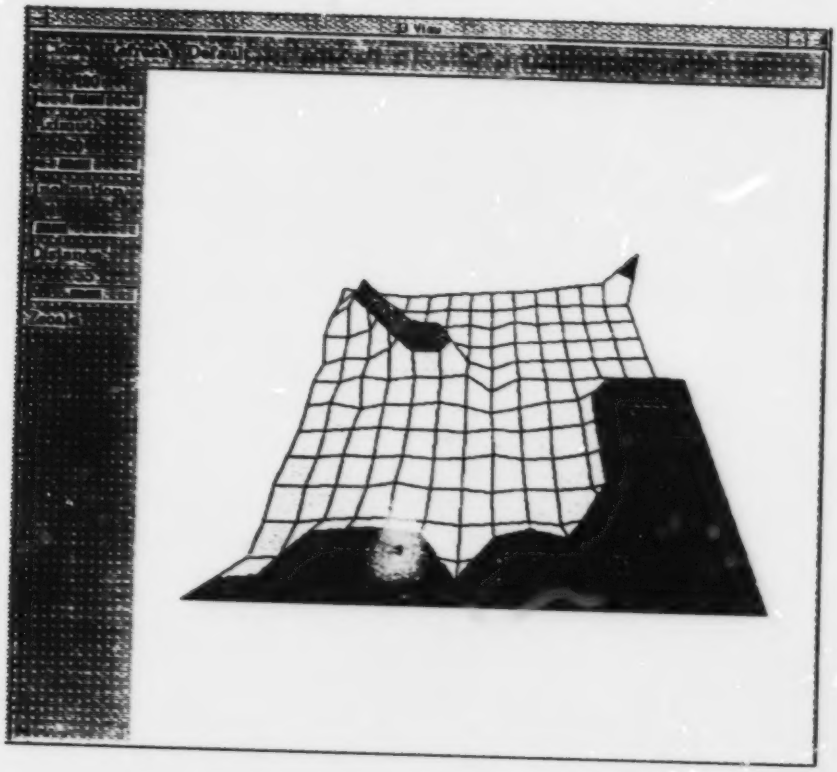

Fig. 4.5 3-D View

5. CONCLUSION

A user-friendly, map-based menu-system spill analysis model has been developed and implemented. It incorporates more than 15 years of modelling expertise from the Danish Hydraulic Institute and the Water Quality Institute. A Graphical User Interface helps minimize human errors during application of the model tool under stressful conditions. Actual spills, e.g. in the Norwegian Haltenbanken area, have been used to calibrate the weathering module, and other modules have been calibrated as well, e.g. using the Ekofisk spill in the North Sea.

A VERIFICATION SYSTEM FOR REGIONAL SEA ICE MODELS IN CANADIAN WATERS

by

TOM YAO
ASA Consulting Ltd., Dartmouth, NS

TOM BROWN
F.G. Bercha and Associates (Alberta) Ltd., Calgary, AB

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Abstract

A standardized verification system for sea ice models is presently under development for the Ice Centre of Environment Canada (ICEC). The verification system will be applied to ICEC's Regional Ice Model (RIM) with specific application to East Newfoundland/Labrador waters and the Beaufort Sea. The study is being funded by the Panel on Energy Research and Development (PERD) and is being directed by the Ice Model Verification Working Subgroup (IVWG).

The verification system will provide an objective, quantitative evaluation of ice model performance for several model forecast outputs including: ice velocity; total and partial (by ice types) ice concentrations; and ice edge location. Some capability for verification of model derived ice pressures is also being sought but there are considerable difficulties in acquiring direct observations of ice pressures over appropriate spatial scales. The verification system consists of two integrated components: a standardized verification methodology and high quality data sets (both input and verification parameters) for which the verification methodology is applied to RIM.

The verification methodology being developed with application to RIM relies on a statistical approach using the following verification measures:

- mean and variance of observation;
- mean and variance of forecast;
- bias between observation and forecast;
- mean square error (MSE) between observation and forecast;
- regression model (slope, intercept, correlation) including parameter uncertainty (error bounds for slope, goodness of fit);
- MSE skill score;
- moments from directional statistics.

The data sets being prepared for use in the verification system consist of two periods of ten days duration in both the Beaufort Sea and East Newfoundland/Labrador waters. For each of these four data periods, accurate data sets are being prepared. These data sets include the necessary input fields, (initial ice concentrations, winds, ocean currents, air and sea temperatures) to drive the model and independent observations (ice concentrations, ice edge location and ice velocities) to compare with model output. The derivation of the data sets has relied heavily on working up information from the best available remotely sensed data sources (SAR and NOAA AVHRR-derived ice velocities and concentrations), model-derived hindcasts to surface winds as well as more conventional surface based measurements.

1.0 INTRODUCTION

1.1 Background

As part of its overall mandate, the Ice Centre, Environment Canada (ICEC) uses a numerical model to aid in forecasting ice conditions in various coastal regions in Canada. The model is termed "The Multi Category Regional Ice Model" (*MCRIM*) and is typically executed to provide two to five day forecasts of ice conditions in the Canadian Beaufort Sea, the Gulf of St. Lawrence, and the Newfoundland and Labrador Coasts. The Regional Ice Model is used in conjunction with observations of ice conditions and forecasts of meteorological conditions to provide these ice forecasts.

RIM was originally developed by Hibler (1979) and adapted by ICEC for its operational requirements in the mid-1980s. Since that time, it has been modified and upgraded to its present status. The model is used to predict ice drift, partial ice concentrations, and ice pressure, and it can also be used to infer the ice edge location. The model is therefore a valuable tool in ice forecasting operations, the results of which are widely distributed and used.

It is important that the forecast made using the Regional Ice Model results be as accurate as possible. Over the past several years, several evaluation studies have been made of RIM results and these are briefly reviewed in Chapter 2. The execution of the model requires a considerable amount of input data in the form of atmospheric and oceanographic data as well as the initial ice data. While errors may arise from errors associated with this input data, it is also possible that errors may arise as a result of the mathematical formulation of the model, and possibly, the actual physics modelled.

Since the installation of *MCRIM*, Canadian Sea Ice Research Activities have included components aimed at modelling sea ice processes, often in relation to oceanographic and meteorological forcing. Research of this type has been conducted by various groups within government research establishments. As a result, in 1987 an Ice Model Working Group (IWG), reporting to the Panel on Energy, Research, and Development (PERD) was formed. This group included representatives from ICEC and the various government research organizations involved in modelling sea ice processes, has met several times to discuss the problems of operational ice modelling. This group identified a need for a program of verification for both the MCRIM and other Regional Ice Models under development. The IWG identified the need for a verification program and formed an Ice Verification Working Subgroup (IVWG) to address the problem of model verification.

A verification system is presently being developed by the authors in collaboration with the IVWG. The first phase of the system development was completed in March 1991 as separate projects for Canadian East Coast waters and the Beaufort Sea (Fissel and Yao, 1991; Brown et al., 1991). A second phase of development addressed at both areas is presently underway, with completion expected in the spring of 1992. (Yao, Brown and Fissel, 1992).

1.2 Objectives

Overall: To provide a consistent and objective system to assess the performance of sea ice models.

The verification system will support the scientific and administrative requirements for operational ice modelling, as developed by the Ice Verification Working Group (IVWG) reporting to the Panel on Energy Development (PERD).

- Scientific -
  - document the quality of model output;
  - document the performance of models for different situations;
  - test the effectiveness of different methodologies;
  - determine the characteristics of model error.

- Administrative -
  - Research - document progress of R&D programs and provide information to direct future R&D priorities;
  - User Requirements - document how effectively user requirements are being addressed;
  - Operations - document strengths and weaknesses within the forecasting system.

2.0 OVERVIEW OF VERIFICATION SYSTEM

The Verification System consists of two major components:

- STANDARD VERIFICATION DATA SETS:
  High quality inputs and verification data sets to drive the model and to provide comparisons with model outputs using:

- STANDARD SET OF VERIFICATION PROCEDURES:
  Verification procedures appropriate to each model output of interest which provide an objective measure of model performance.

The verification system is applied to Regional Ice Model outputs, specifically:

- ICE VELOCITY
- ICE CONCENTRATION (TOTAL)
- ICE CONCENTRATION (BY ICE TYPE)
- ICE EDGE LOCATION

Also, techniques are being developed to provide model output for internal ice stress (in the Multi-Category Regional ice Model - *MCRIM*). The ice stress output will be compared to the very limited quantities of ice stress measurements, as well as forecasts by ice analysis.

3.0 VERIFICATION DATA SETS

Two principal data sets are required for the verification process. The first of these data sets (the output of verification data set) provides the necessary information to execute the verification procedures (see Section 4) for sea ice model output. The second data set (the input data set) provides the necessary meteorological, oceanographic and initial ice concentration data sets required as input to the sea ice model. The nature of the data sources available for the derivation of both the output and the input data sets is such that a number of different sources may be required to provide the necessary spatial and temporal coverage for each parameter.

Ideally both types of data sets should provide observations of the required parameters on a sufficiently dense spatial and temporal grid to minimize errors in interpolation of the data of the model grid locations and the analysis of time intervals.

An extensive review of available data sources for the Beaufort Sea and East Newfoundland/Labrador waters (Figures 1 and 2) was conducted. Particular emphasis was placed on documenting important attributes used in data set selection: accuracy, reliability, spatial coverage, duration and resolution. The selection of the appropriate time periods for the verification process focused on minimization of the data uncertainty for those period over the model domains. This translated into maximizing the available sources during each period, with emphasis, however, on high quality data sources.

3.1 Selection of Verification Periods

Following an extensive review of data availability for both areas (Fissel and Yao 1991; Brown et al., 1991) the periods offering the most promise for the purpose of working up ice model verification data sets were determined to coincide with either extensive oil exploration activities or with large scale oceanographic experiments. Based on 11 potential periods identified in the data review and appraisal process, two data periods were selected for each modelling region:

BEAUFORT SEA:

- 17 to 26 June, 1985
- 18 to 27 August, 1985

EAST NEWFOUNDLAND/LABRADOR:

- 30 March to 9 April, 1985
- 10 to 19 March, 1989.

3.2 Summary of Data Sources

The selection of particular data sources, and the methods used to extract the required information from the data sources, are presented in Yao, Brown and Fissel (1992).

Given the remoteness of the modelling areas, and the often difficult working conditions, much of the data were obtained through remote sensing techniques.

Table 1. Overview of Data Sources for Each Modelling Region

Data Set	Type	Time Resolution	Data Sources	
			Beaufort Sea	East Coast
Ice Concentration	I&V	daily	ICEC Charts	ICEC Charts
		most days	airborne SLAR & SAR	NOAA (north part of area)
		most days	NOAA Sat.	
Ice Velocity	V	most days	NOAA Sat.	NOAA Sat.
		daily	sat. tracked platforms	sat. tracked platforms
		most days (Beaufort)	airborne SLAR & SAR	airborne SLAR & SAR
Ice Edge	V	daily	derived from 1/10 contour from ice concentration data sets	
Ice Pressure	V	daily	drill rig observers	none
Winds	I	6 hourly	Oceanweather	Oceanweather
			BWO	CMC
Ocean Currents	I	constant	historical data	historical data
Other: Air Temperature	I	6 hourly	none	CMC
Other: Sea Temperature	I	two per week	none	METOC

3.2.1 Ice Concentration Data

The primary sources of ice concentration data are the ICEC daily ice charts, airborne remotely sensed data (SAR and SLAR) and satellite data sources (NOAA, AVHRR). The availability of each data type varied considerably in terms of both areal coverage, as shown in the Beaufort Sea region in Figure 1, and on a day-to-day basis within the periods selected. Information on total ice concentration, and partial ice concentration by ice types, was extracted and prepared in a common format for the purposes of model initialization and verification.

3.2.2 Ice Velocity Data

Ice velocity data is one of the primary outputs from sea ice models and, in many cases, may be the most important output parameter. The principal sources for ice velocity data are: ice movements derived from NOAA AVHRR imagery using image analysis systems; ice movements derived from SLAR and/or SAR imagery using manual techniques; and satellite-tracked ice beacons.

3.2.3 Ice Edge Data

Ice edge location data sets are derived from ice concentration data sources noted above. For the purposes of deriving the ice edge, the definition of MANICE (AES, 1989) that ice concentration of less than 1/10th are considered open water, is used in extracting ice edge locations.

3.2.4 Ice Pressure

Actual measurements of ice pressure were not available in either study area during the verification periods selected. Direct measurements of ice pressure, over an ensemble of floes having a total area comparable to the size of a grid cell of a regional ice model are extremely difficult to obtain. Even measurements of ice pressure within a single ice floe or between two adjoining floes pose considerable instrumentation challenges, and such data are rarely obtained. For the present study, some indirect inferences on ice pressure were obtained from experienced ice observers in the Beaufort Sea modelling region during the June and August verification periods.

3.2.5 Wind Data

Wind data fields represent the most important driving force of sea ice in most of the modelling domain. For this reason, it is important that the wind fields provided for model input be available on a sufficiently dense temporal basis and with sufficient accuracy to ensure that the uncertainty associated with this model input is minimized.

In the initial phase of the project, two different sources of gridded wind data were provided: AES Canadian Meteorological Centre (CMC) surface analysis winds were used on the East Coast, while winds derived from the Beaufort Weather Office (BWO) surface pressure charts were used for the Beaufort Sea. In the second phase of the project, Oceanweather Inc. was contracted to prepare higher resolution gridded wind fields for both regions.

3.2.6 Current Data

The major oceanographic data input for ice models is the surface current field for the model domain. Unlike marine winds, it is not possible to obtain time specific current fields over large areas such as the Beaufort Sea or East Coast model domains. Indeed, even the development of a climatic current field for these regions is difficult due to the paucity of historical current measurements, particularly long-term current measurements and data collected when sea ice cover is present. Based on a compilation and survey of available

historical ocean current data sets, mean climatological current data sets were prepared for model input. In the Beaufort Sea, one current field was derived for the prevailing wind conditions present during the verification period, while a second base case of mean climatological current field could be prepared. Particularly in the East Coast region, having comparatively strong ocean currents, the use of climatic ocean current inputs has significant limitations in terms of adequately describing the temporal and spatial variability of the actual ocean currents.

3.2.7 Other Meterological and Oceanographic Data Sets

For the East Coast region only, two other types of gridded data sets were prepared. Air temperatures, as derived from CMC surface analyses were generated every six hours. Sea surface temperatures were derived from twice-weekly charts prepared by the METOC Centre, Department of National Defense, Halifax, NS.

4.0 VERIFICATION PROCEDURES

The framework for model output assessment was developed following the theoretical basis of Murphy and Winker (1987), as developed for meteorological applications in this approach, forecast verification involves a set of forecasts denoted by f and the corresponding observed value denoted by x. The basis for forecast verification is the joint probability that the forecast falls within the range f and $f + df$ and the observation falls within the range x and $x + dx$. In practice the joint probability distribution $p(f,x)$ will be estimated based on a sample of forecasts and observations $\{(f_i,x_i);\ i = 1,\ldots,n\}$.

A suite of statistical parameters are derived (Fissel and Yao, 1991; Yao, Brown and Fissel, 1992) to quantify the model assessment. The statistical parameters are:

- mean and variance of the observations;
- mean and variance of the model output;
- bias between observation and forecast;
- mean square error (MSE) between observation and forecast;
- regression model (slope, intercept, correlation) including parameter uncertainty (error bounds for slope, goodness of fit;
- MSE skill score;

These verification statistics are derived for each of the model outputs. An example of one set of verification results is given in Table 2.

For ice velocity only, an additional ice velocity verification parameter involving moments from directional statistics, is being considered for use in the verification system.

5.0 LITERATURE CITED

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Table 2: Verification Measures for Ice Velocity, 1989

	~12 hour verification	~36 hour verification	~84 hour verification
n	143	143	106
$\langle f \rangle$	(0.24 m s^{-1}, 140°T)	(0.24 m s^{-1}, 140°T)	(0.23 m s^{-1}, 153°T)
$\langle x \rangle$	(0.12 m s^{-1}, 130°T)	(0.12 m s^{-1}, 130°T)	(0.10 m s^{-1}, 147°T)
s_f	0.22 m s^{-1}	0.22 m s^{-1}	0.22 m s^{-1}
s_x	0.16 m s^{-1}	0.16 m s^{-1}	0.14 m s^{-1}
bias	(0.13 m s^{-1}, 150°T)	(0.12 m s^{-1}, 150°T)	0.24 m s^{-1}
RMSE	0.23 m s^{-1}	0.22 m s^{-1}	0.24 m s^{-1}
regression			
b	(0.39, -6°)	(0.40, -5°)	(0.29, 6°)
$\lvert r_{fx} \rvert^2$	0.30	0.31	0.21

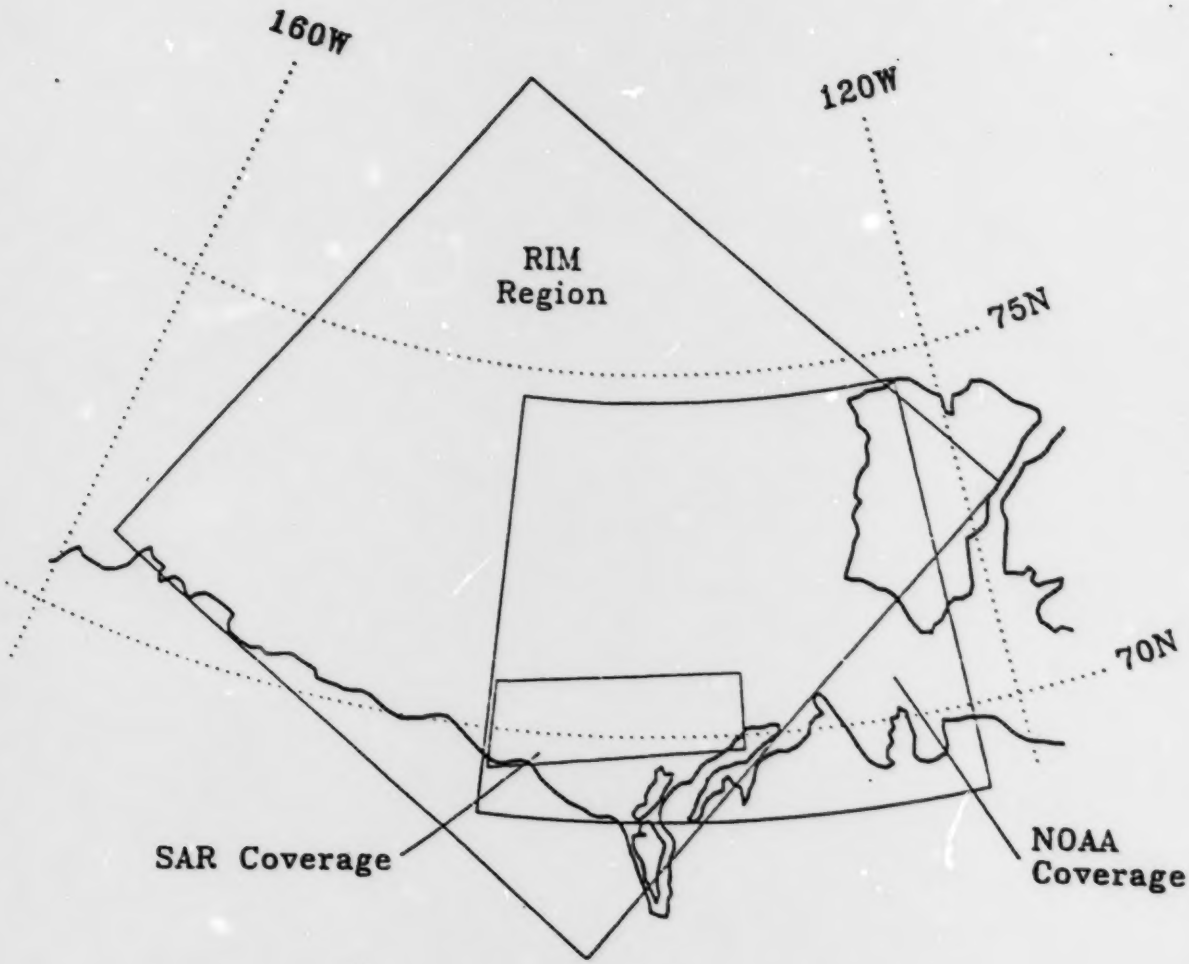

Figure 1 SAR and NOAA Coverage and RIM Region

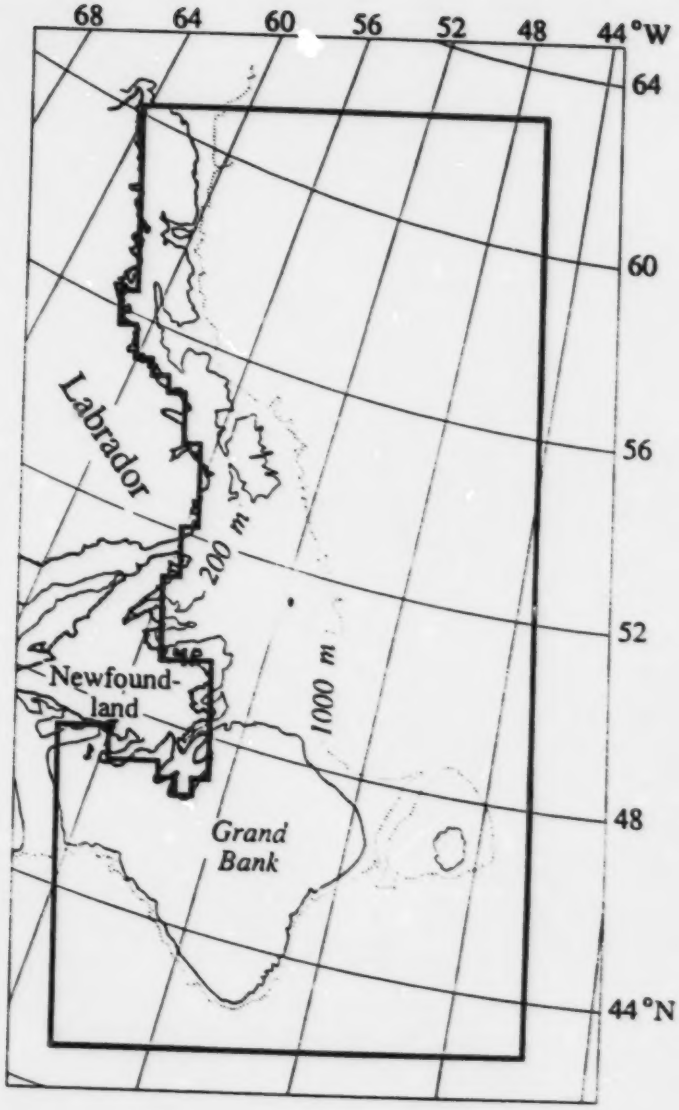

Figure 2 Map of the Labrador and Newfoundland region showing the extent of the model domain selected for this study.

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ANNEX A

Sea Ice Model Review

A STATE OF THE ART REVIEW OF

SEA ICE MODELLING

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Summary

A state of the art review has been carried out on sea ice modelling in Canada considering both the operational requirements and use of ice forecast information, as well as research leading to the refinement of existing models or the development of new models. The review has also considered international aspects of sea ice modelling which may have relevance to Canadian activities in this area. A total of 32 models were reviewed and key parameters documented.

Operational needs were evaluated and users were categorized in three main groups: government, industry and regulatory agencies. A variety of applications and specific output requirements determined whether sea ice models were grouped and reviewed as operational or research-oriented. Additionally, models were categorized into five types, reflecting general applications: (1) ice growth and decay; (2) ice edge prediction; (3) small-scale ice behaviour; (4) regional models; and (5) large-scale climate/global models. Linkages that exist within the research community and between it and the operational users were also included in the review.

This review describes user Canadian requirements for ice forecast information and state of the art sea ice modelling capabilities. It is intended that the document can be used as a tool for the determination of future research efforts and directions.

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1.0 INTRODUCTION

1.1 Background

A variety of predictive models are used operationally to support Canadian marine activities. These models, or products derived from them, are employed by industry, government and regulatory agencies for a variety of applications. The development and refinement of these models is supported through research at government, industry and academic institutions across Canada. The Panel on Energy Research and Development (PERD) supports research to enhance existing operational capabilities through direct funding of modelling research in the areas of sea ice, icebergs, winds, ocean currents, waves and oil spill dynamics. Reflecting the relevance of sea ice modelling to PERD, an operational sea ice modelling working group was organized under PERD task 6.7 in 1987. This group is working to encourage the translation of research results into operational uses.

In recent years, research and development efforts towards improved predictive capabilities for sea ice behaviour have produced a wide variety of models. The models often have different temporal and spatial scales and vary in how they treat the geophysical conditions affecting ice behaviour. In addition, some models have purely research applications, designed to support investigations of physical processes. Others may be operational, oriented to meeting specific needs for forecasting ice conditions. Between these two extremes are a wide variety of models with potential application to a variety of needs.

This document presents a state of the art review of the entire spectrum of sea ice modelling in Canada. The review makes use of a recent survey of the oil and gas industry for PERD to determine operational requirements in ice forecasting.

International modelling efforts have also been considered to identify research which may have particular relevance to operational concerns that have been raised in Canada. While we feel the international review has been reasonably extensive, it is possible that some of the more recent work has been missed since published literature was relied on heavily for this aspect of the review.

1.2 Review Objectives and Approach

A specific objective of the sea ice model review was to detail operational sea ice modelling in Canada and describe how operational needs are being addressed through current research. To achieve this, the approach of the review was to identify:

1) operational users of models and/or forecast products;
2) present and future operational needs;
3) sea ice models in circulation and summarize their stage of development

and their potential for operational implementation;

4) the linkages between the research and operational modelling communities; and

5) problem areas which are restricting the translation of research efforts into models which meet operational needs.

It was beyond the scope of this project to provide a detailed evaluation of each model. While the review has identified the important components of the models reviewed, this was done for the purpose of comparison rather than to define each model or model component most suitable for a given application. The review provides a valuable synopsis of existing capabilities which can be used as the basis for discussion as might arise in a workshop setting where those involved in the use and/or development of sea ice models can discuss strategies for future efforts in this area.

1.3 Review Organization

In Section 2, the review considers operational model usage while in Section 3 it addresses research and development of sea ice models.

In Section 4, some of the important research which is not directly associated with a particular predictive model but which may have importance to future developments in this area is provided. In Section 5, linkages (a) within the research community that serve to facilitate the exchange of ideas between researchers, and (b) between the research and operational communities are considered. Finally in Section 6, an extensive bibliography of material obtained during the course of the review is provided.

In Appendix A individual summary sheets are provided for all operational and research models reviewed and in Appendix B, there is a list of contacts who have expertise in model development or who are using sea ice models in an operational context. The list includes people contacted for this review as well as others not contacted due to project time constraints.

2.0 OPERATIONAL USAGE AND ANTICIPATED REQUIREMENTS

This section documents information gathered on current operational model users, as well as their current and future needs.

Practical aspects and limiting factors must be considered for useful ice forecasts to be obtained operationally from numerical models. A number of factors were considered and identified in describing the operational use of sea ice models. They are as follows:

- groups comprising the model user community (e.g. industry, government, university and regulatory agencies);
- the context and purpose of model usage;
- the type of models being used by various groups;
- the spatial and temporal characteristics of present operational models;
- the limitations of current models in meeting operational needs; and
- anticipated future needs for sea ice models.

2.1 Operational Users

2.1.1 Industry

Operational users of ice forecast information can be divided into three main groups: industry, government and regulatory agencies. They are distinguished by the types of activities engaged in and the levels of ice forecast information required. The main Canadian industry users of ice forecast information are the offshore oil and gas, marine transportation and commercial fishing industries. Within industry, the oil and gas sector has had a direct role in the development of ice forecast models. Despite reduced levels of exploration activity, companies continue to support model development activities. A recent user survey (B. Wright, 1991, pers. comm.) provides a clear indication of where future research efforts should be directed in order to meet the needs of the marine industry generally.

In that survey, it is the general consensus of the Canadian Petroleum Association (CPA) and its member companies "that PERD funding should focus on the strategic or regional and long-term technical areas while industry accepts its responsibility for the more site specific or tactical information needs". A short list of needs and/or research priorities for the Canadian oil and gas industry (i.e. offshore exploration), the marine transportation industry and naval operations is provided in Table 1. The priorities consist of ice detection, ice forecasting and ice management, as well as ice/structure interaction for a number of operational scenarios in the Grand Banks, Beaufort Sea and High Arctic. Ratings of low, medium or high priority were provided by individual CPA users.

Table 1. List of Priorities and Corresponding Levels for the Canadian Oil and Gas Industry.

LOCATIONS	OPERATING SCENARIOS	PRIORITIES	
		ICE DETECTION (D); FORECASTING (F) & MANAGEMENT (M)	ICE/STRUCTURE INTERACTION
Grand Banks	-fixed platform	high (D & F)	high
	-float platform	high (D & F)	med/high
	-pipeline	medium	high
	-tankers/shipping	high (D)	low
	-exploration	medium	low
Beaufort Sea	-platform	low/high	high
	-offshore pipeline	low/high	high
	-tankers/shipping	high (D)	low
	-exploration	med/high	med/high
High Arctic	-fixed platform	low	high
	-float platform	high	medium
	-tankers/shipping	high (D)	low
	-exploration	medium	low

Source: Wright (1991, pers. comm.)

Beyond potential tanker support for the oil and gas industry, the marine transportation sector operate seasonally in the Canadian Arctic and is an important user of ice information. Within the marine sector there is both the commercial fleet and the Canadian Coast Guard. In terms of general operational requirements, the kinds of ice information required by the two groups are similar.

For the most part, shipping companies rely on external interpretations of ice conditions for decision making, rather than conducting hands-on data analysis. Similarly, they are seldom in a position to make use of forecast models directly but rely on third-party products for the information they require. In Canada, the Ice Centre within the Atmospheric Environment Service, Environment Canada has a specific mandate to provide ice information support for marine operations. An exception to this reliance on outside information is Canarctic Shipping Company Limited which has developed its own ice research group to support marine operations.

The commercial fishing industry also makes use of ice information products to plan trawler activities. Once again, the fishing industry relies on third-party information obtained directly through the Ice Centre and through the Coast Guard Ice Operations Office.

2.1.2 Government

Among Canadian government users or potential users of ice models or ice forecast information are AES, Ice Branch and AES, Canadian Meteorological Centre. AES, Meteorological Services Research Branch played an important role in past developments of AES' Regional Ice Model (RIM).

RIM is currently used routinely at the Ice Centre in Ottawa to assist ice forecasters in the preparation of daily ice analysis charts. RIM is also used to generate a 48 hour regional ice forecast for the Alaskan coast. The Ice Centre utilizes a variety of ice growth models to assess ice freeze-up and ice growth at various points along Canadian waterways.

In addition to its role as an operational user, the Ice Centre supports ongoing efforts to improve its ice forecast capabilities.

2.1.3 Regulatory Agencies

Potential regulatory agency users of ice forecast information include the National Energy Board - Canadian Oil and Gas Lands Administration (NEB/COGLA), the Canada Newfoundland Offshore Petroleum Board (CNOPB) and the Canada Nova Scotia Offshore Petroleum Board (CNSOPB). The Canadian Coast Guard also has jurisdiction for regulation of the marine industry in the area of pollution prevention and ship safety. In this capacity it may have requirements for ice forecast information to direct commercial shipping activities.

2.2 Operational Needs

According to Denner and Mendenhall (1982) ice forecasting services are required for several time frames:

1) tactical (< 24 hrs);
2) strategic (1-3 days);
3) medium term (15 days);
4) long-term (30 days); and
5) seasonal outlook (3-4 months).

These levels of service are generally applicable to all three user categories.

2.2.1 Output Requirements

The necessary requirements for operational forecasting are dependent on:

- the type of activity and/or operation, and
- the geographical domain in which the operations will take place,

while the ability to provide forecasts of sea ice movement from operational models depend on:

- the spatial and temporal scales involved, and
- the accuracy required.

In the case of the oil and gas industry, user requirements for ice information include forecasts of hazard occurrence and ice movements with a temporal scale of tens of hours. Forecasts could include the following: (1) the break-up season until freeze-up (open water conditions); (2) fall until late winter (for pack ice conditions); and (3) winter landfast ice movements. In addition, models must be practical in the sense that input requirements, model initialization and model execution can be done routinely as part of normal operational activities. Model results must be reliable and provide sufficient information for the intended application.

Short-term regional forecasting requirements of the oil and gas industry include a information at spatial scales of 100-300 nm on time scales ranging from 1-2 days to 1 week. Positioning accuracies for ice edge definition or internal ice regime definition must be on the order of 5-10 nm. On the other hand, long-term forecasting requires a spatial scale that permit prediction of regional occurrence of sea ice by general type (e.g. thin ice, thick ice, old ice of low, moderate <u>or</u> high concentrations) with a temporal scale that may range from monthly to seasonally. Compared to short-term forecasts, appropriate accuracies for long-term forecasts require the definition of light, average or heavy ice seasons.

The marine transportation has a requirement for ice forecast information over a wide range of time scales. Seasonal outlooks and long-term forecasts of ice break-up are important in planning seasonal operations (B. Gorman, 1991, pers. comm.). On shorter time scales information regarding ice concentration and zones of ice pressure (convergent or divergent ice conditions) are also important (Capt. J. Eggenberger, 1991, pers. comm.). Forecasts on the order of 2 days are useful for tactical decisions while 3 to 4 day forecasts are necessary for strategic planning.

The fishing industry relies on ice information to direct trawlers to potentially attractive fishing locations. Experience has shown that along the east coast, fish congregate near the ice edge. Knowledge of present and forecast ice behaviour is immediately relevant to fishing industry operational planning.

AES, Ice Branch has a mandate to provide timely and accurate ice information for Canadian waters on an operational basis and to provide a national archive for the data. Included in this mandate is the requirement to provide prognostic ice information to support all Canadian marine activities.

Historically, Ice Branch has acted as both developer and user of ice forecast models and has a continuing interest in model developments to meet their forecast objectives. A description of AES, Ice Branch priorities for sea ice modelling is provided in Table 2.

Table 2. List of Priorities for AES, Ice Branch.

LOCATIONS	PRIORITIES	
	ICE-RELATED	MODELLING
Gulf of St. Lawrence; Grand Banks; Labrador Sea; Beaufort Sea	partial ice concentrations; roughness; floe size; ice state; edge location; pressure	-focus on 2-5 day forecasts; -sophisticated thermodynamic models & a better representation of the ocean; -use of ice dynamic models; -need higher resolution models with more appropriate ice rheologies; -incorporate research results.

Source: Notes from PERD 6.7 comm. meeting held in January 1991.

2.2.2 Operational Considerations

Most sea ice models have been designed as research tools and operational requirements have rarely been considered in their initial stages of development. Frequently their purpose is towards understanding physical processes rather than forecasting precise future ice conditions. While this understanding may be of interest to the operational user, his primary concern is more likely to be for what can be expected at some time in the future. For some operations, this question is asked repeatedly and a reliable answer is desirable on an equally frequent basis. While, forecast reliability is important, the measure of reliability may vary depending on the operation and the type of ice information required.

Aside from difficulties inherent in modelling physical processes, for a model to be used operationally, the following operational constraints also need to be considered:

- The model should have some means of directly incorporating observed and analysed ice information at a point when the model is initialized.

- Forecasts cannot rely heavily on real-time data inputs such as "high-

resolution" currents or direct on ice measurements if provision of these data is not possible on a routine basis.

A number of observed parameters are required for sea ice forecasting. These include small and/or regional scale drift, ice concentration, ice thickness, ice edge, and ridging, lead-orientation and fractional area characteristics. Some of this information can be provided by means of remote sensing. Although remote sensing observations have their own limitations, the use of sensors on aircrafts and satellites has greatly improved the quality of data available for input to ice forecast models.

- Constraints imposed by the availability or quality of data required to drive the models or computational factors may require compromises in model formulation.

- Model results must be available in a timely fashion. Computational requirements or the time and effort required to process input data may affect how well a given model can meet operational needs.

2.2.3 Operational Models Reviewed

The identification and description of existing operational models was an important component of the review. Recognizing that models have been developed for various applications, the models reviewed have been organized into five main subsections: ice growth and decay; ice edge position; small-scale ice behaviour; regional ice characteristics; and global ice behaviour. Several of the models may serve more than one application and since these categories are somewhat artificial, a particular model may fit into more than one subsection.

A summary of operational sea ice models that were considered in the review is provided in Table 3. The type of model, its applicability and the users and/or model developers were also identified. For each of the models shown in Table 3 a detailed fact sheet is provided in Appendix A along with similar information for research models discussed in Section 3.0 (note: Appendix A features a detailed description of key parameters for 32 sea ice models).

Table 3. Summary of Operational Models

Sea Ice Models	Type	Applicability	Users
AES - Regional Ice Model (RIM)	R	O; R	fed. gov't (AES)
Amoco/Canmar Ice-Forecasting	S	O	industry
Kozo - Sea-Ice Movement Forecasting Model	S; R	O	university (USNA/Alaska)
Pritchard - Ice Edge Model	E	O; R	univ./priv./indus. (NPS/firms/ARCO)
NOARL - High-Resolution Sea-Ice Model (RPIPS-B MODEL)	R; E	O; R	U.S. gov't (NORDA)
El-Tahan - Ice-Floe Drift Model	E	O	private firm
AES - FDD Ice Thickness Model	G	O	fed. gov't (AES)
AES - Heat Budget Ice Thickness Prediction Model	G	O	fed. gov't (AES)
AES (Billelo) - N-value Freeze-up Model	G	O	fed. gov't (AES)
AES - Analog Freeze-up and Break-up Method	G	O	fed. gov't (AES)
Seaconsult - Long Range Sea Ice Prediction Model	R	O	fed. gov't (AES)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale.
Applicability: (O) - Operational; (R) - Research.

3.0 RESEARCH AND DEVELOPMENT OF SEA ICE MODELS

The level of effort associated with modelling large-scale sea ice behaviour has grown substantially in the last 15 years from some of the initial models that were developed (e.g. Coon et al., 1974; Semtner, 1976; Hibler, 1979; and Parkinson and Washington, 1979). Highly complex models are being developed to deal with specific problems and are constantly being refined to better account for the physical world and to improve model efficiency.

The purpose of this section of the review is to document the research and development work that is being done, focusing first on efforts in Canada and then on international research. Undoubtedly, the review does not include every model that has been developed. However, it does include the critical work that has become the basis for further research and deals with recent developments that are at the "cutting edge" of sea ice modelling.

As for the operational models reviewed, detailed fact sheets for the research models reviewed can be found in Appendix A. These fact sheets present in a standardized format the basic physical and computational aspects of the models to facilitate comparison.

Table 4 provides a summary of the research-oriented models that were reviewed. For each model its position in the five general categories is provided along with an assessment of its stage of development. For most of the models, it was possible to determine whether some sort of sensitivity analysis has been undertaken. Where a quantifiable assessment is available, it has been noted. Finally, an attempt has been made to evaluate what sort of linkages have been established to facilitate transfer of information by the researcher(s) associated with a particular model. The linkage-related information will be discussed more fully in Section 5.

While a detailed description of model parameters is beyond the scope of this project, some basic parameters are presented in Table 5 for comparison. The models shown in Table 5 include all dynamic/thermodynamic research models considered in this study; excluding the ice growth models and the Seaconsult Long Range Forecast Model.

The information in Table 5 illustrates that:

- researcher's have used a wide range of values for the different parameters;
- some parameters are not held as constants for all models; and
- values for some constants were not provided in the literature surveyed.

Table 4. Summary and Status of Research Models Reviewed

Sea Ice Model	Type	Stage of Development	Sensitivity Analyses	Research Operation Linkages
AES/Gabison - Thermodynamic Ice Growth and Decay Model	G	D	Y	PUB
Miller - Seasonal Sea Ice Growth Model	G	D	Y	PUB; PRES
Mellor - MIZ Coupled Ice-Ocean Model	E	UK	Y	PUB
Ikeda - Labrador Shelf Dynamic/ Thermodynamic Sea-Ice Model	R	D/U	Y	PUB; PRES
Ikeda - Coupled Ice-Ocean Model	R	U/O	Y	PUB; PRES
IOS - Beaufort Sea Ice-Ocean Model	R	D	N	PRES
Waterloo - Short-Term Sea-Ice Motion Model	R	U/O	Y	PUB
Lemke - Ice/Ocean Model with Mixed Layer Pycnocline Model	R	U/O	Y	PUB
Lu - Mesoscale Sea-Ice Model	R	U/O	Y	PUB
Omstedt - Coupled One-Dimensional Sea Ice-Ocean Model	R	O	Y	PRES
Houssais - Thermodynamic Coupled Ice-Mixed Layer Model	R	UK	N	PRES; PUB
Overland & Pease - Coastal Sea-Ice/Barotropic Ocean Model	R	U/O	Y	PUB
Seaconsult - Long Range Sea Ice Prediction Model	R	O	Y	IR
Simple Steady-State Coupled Ice-Ocean Model	C	U/O	N	IR; PUB; PRES
Hibler Coupled Dynamic/Thermodynamic Model	C,R	U/O	Y	PUB; IR; O; PRES
Hibler & Bryan - Diagnostic Ice-Ocean Model	C	O	Y	PUB; IR
Flato & Hibler - Cavitating Fluid Sea Ice Dynamics Model	C,R	O	Y	PUB
Semtner - Dynamic/Thermodynamic Sea-Ice Model	C	UK	Y	PRES
Semtner - Arctic Sea Ice and Ocean Circulation	C	O	Y	PUB
Parkinson & Washington - Large-scale numerical model of sea-ice	C	U/O	Y	PUB
Walsh & Zwally - Dynamic/Thermodynamic Sea-Ice Model	C	UK	Y	PRES
Riedlinger - Arctic One Dimensional Ice-Ocean Model	C	O	N	PUB

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Stage: (O) - Ongoing; (U) - Updated from previous version; (D) - Discontinued; (UK) - Unknown; (OP) - Operational.
Sensitivity: (Y) - Yes; (N) - No.
Linkage: (PUB) - Results published; (IR) - Results in internal report; (PRES) - Results presented at conference/workshop; (O) - Other.

Table 5. Comparison of Some Basic Model Parameters

Sea Ice Model	Q_a	Q_w	C_a	C_w	P^*
Mellor - MIZ Coupled Ice-Ocean Model	N/A	M	2	3.8	N/A
Ikeda - Labrador Shelf Dynamic/Thermodynamic Sea-Ice Model	V	V	1.2	N/I	0.5
Ikeda - Coupled Ice-Ocean Model	N/I	V	N/I	6	1
IOS - Beaufort Sea Ice-Ocean Model	N/I	N/I	N/I	N/I	N/I
Waterloo - Short-Term Sea-Ice Motion Model	N/A	N/A	1.5	4	2
Lemke - Ice/Ocean Model with Mixed Layer Pycnocline Model	N/A	M	1.2	5-5.5	2.75
Lu - Mesoscale Sea-Ice Model	N/A	N/A	1.55	5.5	2.75
Ornstedt - Coupled One-Dimensional Sea Ice-Ocean Model	M	M	N/I	N/I	2
Houssais - Thermodynamic Coupled Ice-Mixed Layer Model	V	V	V	V	N/I
Overland & Pease - Coastal Sea-Ice/Barotropic Ocean Model	N/A	N/A	2.8	1.8	1.6
Simple Steady-State Coupled Ice-Ocean Model	3.5-10.0	5-20	N/A	N/A	N/A
Hibler Coupled Dynamic/Thermodynamic Model	N/I	N/I	1.2	5.5	0.5
Hibler & Bryan - Diagnostic Ice-Ocean Model	N/I	V	V	V	V
Flato & Hibler - Cavitating Fluid Sea Ice Dynamics Model	N/A	V	V	V	V
Semtner - Dynamic/Thermodynamic Sea-Ice Model	N/I	0-275	1.8	1.8	V
Semtner - Arctic Sea Ice and Ocean Circulation	N/I	0-275	1.8	1.8	V
Parkinson & Washington - Large-scale numerical model of sea-ice	V	2-25	2.4	V	V
Walsh & Zwally - Dynamic/Thermodynamic Sea-Ice Model	N/I	2	1.2	5.5	V
Riedlinger - Arctic One Dimensional Ice-Ocean Model	N/I	V	2.7	5.5	N/A

Q_a - Atmospheric Heat Flux (W m^{-2})
Q_w - Oceanic Heat Flux (W m^{-2})
C_a - Air Drag Coefficient ([x 10^{-3}], non-dimensional)
C_w - Water Drag Coefficient ([x 10^{-3}], non-dimensional)
P^* - Ice Strength Constant ([x 10^4], N m^{-2})

M - modelled parameter
V - variable
N/A - not applicable
N/I - insufficient information or not available

The following subsections discuss the models within the different categories, providing a general discussion of the approach employed. The complexity of even the most basic models dictates that close consultation of the noted references will be required for more detailed information.

3.1 Ice Growth Models

The physics of ice growth and decay is considered in sea ice models generally, but in addition, several models have been developed to deal with site-specific ice growth as an important parameter in and of itself. As ice growth is an important operational consideration, models of this sort are considered separately. The research models reviewed here compliment several operational models which are utilized by AES (Ice Branch) for the forecast of freeze-up and ice thickness prediction at various Canadian sites.

In addition to several operational models employed by AES, research-oriented ice growth models by Gabison (1987) and Miller (1981a; 1981b) were reviewed. Gabison presents a thermodynamic model based on earlier work by Maykut and Untersteiner (1971) which includes a coupled mixed layer ocean model. Miller's work entailed the application of synoptic-scale climatological data and site-specific characteristics such as snowfall to an energy budget conservation model. Both researchers document diagnostic assessments of model sensitivity, as well as verification efforts for selected Arctic sites.

Some recent research at BIO has led to interesting contributions to the development of ice growth models. For example, G. Budgen's work at BIO (1991, pers. comm.) has dealt with the effect of circulation-induced heat advection on the AES heat budget approach for predicting freeze-up in the Gulf of St. Lawrence. In areas where the circulation is relatively consistent, it is possible to estimate the advection term from readily available current and sea surface temperature maps to improve freeze-up and ice growth predictions.

Work by I.K. Peterson and S.J. Prinsenberg (1991, pers. comm.) has been done to verify freezing-degree day (FDD) models with ice growth rates obtained by satellite-tracked ice beacons. Analysis of data from offshore Labrador indicates that snow cover is an important parameter in ice growth models. According to Prinsenberg, additional data analysis from landfast ice stations along the Canadian east coast and Arctic reveal that the empirical constants of FDD models vary slowly with location as a result of changing snow cover conditions. An ice beacon deployment programme has been established to verify the application of FDD ice growth models for offshore pack ice along the Canadian east coast in the winters of 1991 to 1993.

3.2 Ice Edge Prediction Models

A few models have been developed to deal specifically with ice edge prediction. They included models by El-Tahan and Warbanski (1987) and Pritchard et al. (1990) while others (e.g. C. Tang [BIO] and G. Mellor [Princeton University]) are looking at Marginal Ice Zone (MIZ) models which consider ice-ocean interaction at the ice edge.

The El-Tahan model is oriented towards the strategic ice management needs of the East Coast oil and gas industry and is fully operational. The model is driven by surface winds (observed and forecast), ocean currents (a residual current and a time varying current derived from the wind velocity), as well as the observed ice edge position when available. A brief paper (El-Tahan and Warbanski, 1987) describes the model and provides an evaluation of the model performance.

Pritchard et al. (1990) have developed a coupled ice-ocean dynamics model to provide the Arctic offshore oil and gas industry with a model capable of forecasting ice conditions and ice edge motion on scales of 5 to 7 days. The model incorporates an adaptive grid that can be either Lagrangian or Eulerian at points away from the ice edge. The coupled ocean model provides thermodynamic input to the ice model, as well as describing the mixed layer within the MIZ. Comparison of modelled results in the Bering Sea with observations indicate ice edge agreement to within 5 km/day.

A regional model developed at the U.S. Naval Oceanographic and Atmospheric Research Laboratory (NOARL), is being used operationally by the U.S. Naval Polar Oceanography Center (NPOC) in preparing its weekly ice concentration forecast for the Barents Sea. Included in this is a coarse estimate of ice edge (model resolution is 25 km). While this estimation of ice edge has some operational relevance, it is certainly not, within the specifications in Subsection 2.2.1, pertaining to Canadian offshore industry requirements.

Tang (1991, pers. comm.) is currently working on a wind-forced ice motion model for the Newfoundland MIZ. The model is coupled to a 3-dimensional ocean model and is designed to forecast ice-ocean behaviour over periods of days. Work is under way to validate the model results with plans for intensive data acquisition during the next Canadian Atlantic Storm Program (CASP II). Future modifications to the model will include improved thermodynamics.

The work by Mellor and Kantha (1989) also focuses on ice-ocean processes in the MIZ. Modeling efforts include the development of a two-dimensional coupled ice-ocean model for the MIZ with testing being done for winter ice conditions in the Bering Sea using MIZEX West data.

While the latter two researchers are not the only ones engaged in modeling research

related to MIZ's, their work illustrates the type of research being done. In addition, several of the models to be discussed under subsection 3.3 and 3.4 also incorporate concepts which consider unique MIZ characteristics and which are potentially relevant to the prediction of ice edge behaviour.

3.3 Small-Scale Ice Models

The definition of a small-scale model is somewhat inexact, except to say that a model in this category considers ice behaviour over scales of tens of kilometres rather than hundreds of kilometres in the case of regional or mesoscale models. As noted earlier, operational forecast requirements at this scale are seen by some operators as being their own responsibility and they have, in the past, invested considerable effort into predicting ice motion on time scales relevant to tactical decision making (eg. tens of hours).

A few small-scale models were identified in the course of this review. These include a small-scale research-oriented model to forecast sea ice movement in Bering Strait, developed by Kozo et al. (1987) and a model developed by Thompson et al. (1988; 1990) for the Southern Beaufort Sea. The latter is, by the terms of this review, more appropriately classified as a regional model and is described under Subsection 3.4. In addition to specific models, considerable peripheral research relevant to small-scale ice behaviour is discussed in Section 4.0.

The work by Kozo et al. uses surface atmospheric pressure data from a triangular station network surrounding the Bering Strait to derive hypothetical geostrophic winds. These are then used in conjunction with net daily sea ice movement estimates obtained from NOAA satellite imagery to project an empirical 12 hr forecast of sea ice movement.

Eley (1986) documents small-scale model efforts in support of the Beaudril Kulluk in the Beaufort Sea. A variety of ice drift forecast methods are described along with the results of a brief verification program. This ice forecasting is reflective of the type of information required in an operational setting and of the kinds of models which can be reasonably utilized.

3.4 Regional Ice Forecast Models

By far the largest number of research models reviewed, was in the category of regional or mesoscale models. These models, as the category name suggests, are designed to model ice conditions over spatial scales on the order of hundreds of kilometres. Temporal scales may vary from short-term (on the order of days) to long-term (seasonal to annual forecasts).

In Canada, considerable effort is being focused on the refinement of regional models to assist AES in the preparation of daily ice information for several regions. Support is provided principally by research scientists at the Bedford Institute of Oceanography (BIO) in Dartmouth, N.S. and the Institute for Ocean Sciences (IOS) in Sydney, B.C. Additional research is being undertaken at academic institutions including the University of Waterloo - Department of Civil Engineering and McGill University - Centre for Climate Change and Global Research.

Several areas of investigation can be identified:

- coupling of ice and three-dimensional ocean models (M. Ikeda, BIO);
- improvement of thermodynamic forcing (M. Ikeda and C. Tang, BIO);
- better parameterization of MIZ characteristics (C. Tang, BIO);
- integration of remotely-sensed ice velocity data into models (M. Ikeda and C. Tang, BIO);
- development of shallow water (<40 m), ice-ocean models for coastal ice regimes (P. Budgell, formerly at IOS);
- short-term ice response (N. Thompson, University of Waterloo).

Typically, efforts are being concentrated geographically in the Beaufort Sea and off the east coast, including the Labrador Sea and Newfoundland Shelf regions. The stage of development of the models varies considerably, although it is possible to say that, at the very least, considerable work needs to be done in the area of model verification before operational implementation commences.

From the work reviewed, state of the art international effort is consistent with research interests in Canada. Important areas of research include coupling of improved ocean models to sea ice models (Hibler and Bryan, 1987; Lemke et al., 1990) and improvements of MIZ modelling capabilities (Lu et al., 1989). The work of Overland and Pease (1988) in modelling coastal ice process may have application to Canadian operational needs.

In an effort to improve seasonal ice forecasts, AES in conjunction with Seaconsult Ltd. has recently developed a Long Range Ice Forecast Model. The model employs Empirical Orthogonal Functions to evaluate monthly and seasonal ice severity against analog years. Model base data includes historical sea level pressure, upper level 700 mb and 500 mb geopotential height, surface air temperatures and ice concentration data. A database of monthly values has been compiled for a region centred over Labrador, extending latitudinally from 40°N to the pole and longitudinally from 10°W to 110°W. Ice indices of areal extent and volume of ice present are calculated for subdivided regions including the Grand Banks, Labrador Sea and the Gulf of St. Lawrence.

Using a minimum of four months data (historical or prognostic) to drive the model,

analog years are determined on the basis of eigen function coefficients. The model has been installed at Ice Centre, but is not yet fully operational.

3.5 Climate/Global Models

Much of the early work in the development of ice models focused on modeling the dynamic and thermodynamic behaviour of ice in the Arctic Basin. Interest in this area remains high, particularly with respect to the role an ice cover plays in climate change. Some of the early model research (e.g. Hibler, 1979; Parkinson and Washington, 1979) has been used as a base for extensive work that has led to operational models of regional ice behaviour (Nerella et al., 1988 and Preller and Posey, 1990).

Considerable research in climate modelling is now being concentrated towards the integration of more sophisticated ocean models (Hibler and Bryan, 1987; Semtner, 1987; Reidlinger et al., 1990) with a given sea ice model and specification of a realistic snow cover on the ice surface (Semtner, 1987; Reidlinger et al., 1990). While greater realism is being introduced into the models, it is often at the expense of greater computational costs. Flato and Hibler (1988) have looked at using a cavitating fluid approach to the ice rheology in modelling the Arctic Basin ice cover. This approach provides significant computational benefits (the model runs approximately two times faster than with a viscous-plastic formulation) but at the expense of less detail in the ice thickness.

The Centre for Climate and Global Change Research at McGill University, directed by Dr. L. Mysak is involved in sea ice modelling for the purpose of evaluating climate change. Work includes the use of several models including a steady state coupled-ice ocean model described by Willmot and Mysak (1989). The model has been applied to the Greenland Sea (Wood and Mysak, 1989) and recently to the Labrador Sea/Davis Strait region (Mysak et al., 1991).

It can be demonstrated that from past experience that model research at scales of concern to climate modellers can yield advances of relevance to operational needs but that these may not necessarily be achieved over short-time scales. The same situation is likely to continue. As an example, Flato and Hibler (1990) have taken some of their research on a cavitating fluid approach and applied it to MIZ ice modeling where it has been noted that a viscous-plastic ice rheology may not be the most appropriate.

4.0 PERIPHERAL RESEARCH EFFORTS

Considerable research presently conducted focuses on specific formulations or parameterizations required to improve ice modelling capabilities. Some of the issues identified by the PERD 6.7 Ice Working Group (minutes from PERD 6.7 meeting, January 1991) requiring better parameterization include the following:

- Air/Ice Drag Relationship

  B. Burns (1990) has investigated the possibility of using Synthetic Aperture Radar (SAR) data to distinguish sea ice regimes with differing air/ice drag properties. Her work attempts to exploit SAR sensitivity to surface roughness to obtain indicators of atmospheric drag variations over sea ice. While an important issue for the modeller is how to implement a variable drag coefficient into the model, the work by Burns may provide a means of obtaining operationally useful information as input to this parameter.

- Ice/Water Drag Relationship

  The work by D. Topham at IOS considers the ice/water drag for individual ice topographic features and additional data collection programs have been conducted recently to assist in addressing how the drag around an individual feature can be related to the specification of drag on scales more appropriate to ice/ocean dynamic models (e.g. 5-10 km). The results of this work remain to be published.

- Ice Melt

  Considerable research is being conducted on a number of fronts to improve the thermodynamic aspects of existing models. M. Ikeda (1991, pers. comm.) sees this as an important aspect of his ongoing research to develop a regional ice-ocean model for the Labrador Sea/East Newfoundland area. Plans include evaluation of a more sophisticated three-dimensional ocean model which will allow for better simulation of sea ice thermodynamics.

  C. Tang (1991, pers. comm.) is also working on improvements to the thermodynamics of a wind-forced ice motion model for the Newfoundland MIZ. Efforts are to include parameterization of the ice edge melting process. Validation data collection is planned for CASP II.

  S.J. Prinsenberg at BIO is investigating ice-edge melt rates by using ice beacon trajectories and ice edge location data from ice charts. Horizontal and vertical melt rates for advancing and retreating ice edged were observed and parameterized in relation to ice velocities.

- Ice Growth

There appears to be little direct research into the development of ice growth models for the prediction of site-specific freeze-up and ice thickness. Some recent investigations have been conducted by G. Budgen at BIO (1991, pers. comm.) as to the effect of circulation-induced heat advection on the AES heat budget approach for predicting freeze-up in the Gulf of St. Lawrence. In areas where the circulation is relatively consistent, it is possible to estimate the advection term from readily available current and sea surface temperature maps to improve freeze-up and ice growth predictions. This work remains to be published.

Recent updating of FDD models using Ice Centre (AES) landfast ice data and satellite-tracked ice beacon data are being conducted by S.J. Prinsenberg and I.G. Peterson at BIO. The work has shown the importance of snow cover in ice growth models.

- Ice Rheology Implementation

The question of ice rheology is one being addressed by several researchers internationally. Investigations by Leppäranta and Hibler (1985) considered how ice floe interaction at the ice edge might affect ice velocity. In doing so, they considered a non-linear plastic ice rheology and observed modification of the MIZ ice and ocean dynamics. Work by Shen et al. (1987) explored the suitability of a floe collision ice rheology for the MIZ. This work has been expanded on by Lu et al. (1989) and implemented in a model designed for the MIZ ice regime of the East Greenland Sea (Lu et al. 1990). Work by Flato and Hibler (1989; 1990) explored the application of a cavitating fluid approach to the modelling of MIZ ice behaviour.

- Surface Roughness/Ice Pressure

The Canadian National Research Council (R. Frederking, 1991, pers. comm.) is conducting research into aspects of surface roughness parameterization. The work is focusing on ice rubble formation in pressure situations. The ice is treated as a granular material and the ridge building/rubbling process is observed to evaluate ice feature geometry and size based on loading forces. The goal is to produce physical and analytical models capable of modeling the ridge building process. Currently, discrete element models are being evaluated. As the deformation process acts as an important energy sink, the work being done by NRC could serve as an important component of forecast models.

Work by Shinohara (1990) in developing a redistribution function applicable to dynamic ice models, supports the work being done by NRC. The approach

taken by Shinohara is based on the assumption that work done by the internal stress of sea ice is used to pile up ice and to reduce its overall concentration. In applying the redistribution function to the model proposed by Hibler (1979), calculated ice velocities and ice growth increased up to 50%.

Additional work is being done at NRC to assimilate data on pack ice dynamics for the Arctic. The data will be particularly useful for verification of modelled ice pressure and ice redistribution.

- Ice State

Only limited information was obtained which indicated research was being undertaken to evaluate ice state and associated mechanical and thermal properties. N. Sinha (NRC) is conducting research dealing with the mechanical properties of level ice sheets in the decay phase. The work may have application to thermodynamic aspects of sea ice modelling efforts.

NRC has also done some work in the area of thermo-consolidation looking at the ice refreezing process. Past field measurements by K. Croasdale (Esso Resources) represent the best observations to date. This is an area which could be explored further and which may offer potential insight to modelling problems.

S. Prinsenberg and I. Peterson at BIO have collected salinity and temperature data beneath pack ice off the Labrador coast since 1987 and from the ice since 1989. The data was collected in order to determine the relationship between ice growth, ice extent and oceanic properties necessary for updated FDD models. Preliminary results suggest that higher salinity values are observed in pack ice than values currently used in ice growth models.

- Ice Drift

I. Peterson and S. Prinsenberg at BIO are using ice drift data collected from satellite-tracked ice beacons and satellite image analysis to parameterize the contribution of ice motion by wind and currents. Results for the Labrador Sea/Grand Banks area indicate that the wind speed effect on ice motion can be parameterized as 1.8% of the geostrophic flow for modelling purposes. Further work is under way to evaluate the affect of wind direction on ice motion.

Some additional peripheral issues noted during the review which are relevant to the issue of operational and research sea ice modelling include:

- Lagrangian versus Eulerian Formulation

Most existing operational and research models employ a Eulerian formulation, largely in response to computational constraints. The model developed by Pritchard et al. (1990) to forecast sea ice edge movement in the Bering Sea employs a combined Lagrangian and Eulerian approach, using a Lagrangian formulation near the ice edge while in from the edge a more computationally efficient Eulerian approach could be employed.

- Computational Developments

As models increase in complexity, computational requirements tend to increase as well. Several of the larger research models are optimized to run on large super-computers (for instance, Semtner, 1987). Mindful of the computational constraints, others have experimented with formulations to simplify the numerical calculations. As noted previously, Flato and Hibler (1989;1990) have worked with a cavitating fluid constitutive ice relation which has resulted in improved computational efficiency. Similarly, Lu et al. (1990) utilize moving boundaries between ice regimes within their MIZ model to specify what type of constitutive law is used for given ice conditions. In the process, computational requirements are frequently reduced when a numerically simpler floe collision rheology can be used near the ice edge.

- Standardized Verification Procedures

In an effort to develop procedures for evaluating the performance of their Regional Ice Model (RIM), AES,Ice Branch has undertaken a PERD-sponsored study to develop standardized verification procedures and to compile comprehensive input and verification data sets for each RIM ice output parameter. In developing the verification procedures, a key objective was to devise a verification scheme that could also be applied to other models, readily facilitating the comparison of model performance. Verification and data sets were compiled for the Beaufort Sea and Labrador Sea/East Newfoundland model domains with possible additional data sets to be developed in the future.

5.0 LINKAGES WITHIN AND BETWEEN RESEARCH AND OPERATIONS

The issues of linkages to facilitate the transfer of information between researchers and to the operational community cannot be separated from a description of the sea ice models themselves. Details on the model fact sheets in Appendix A frequently indicate the cross-pollination between researcher's that lead to new hybrid models. Similarly, in considering the operational models listed in Table 3, most of them have originated from what was originally a research application.

5.1 Internal Research Linkages

From the information describing recent and current research efforts, it is clear that interaction and exchange of information between researchers is essential. The number of published descriptions of modelling efforts which employ some aspect of the work pioneered by Hibler in the late 1970's substantiate this. This information exchange is equally valid in other cases.

Having said this, it is not as clear how this exchange takes place. However, it seems that personal communication and a reliance on published material and conference presentation are the main mechanisms for this exchange. From conversation with Canadian researchers, the exchange tends to occur informally and on an ad hoc basis.

5.2 Research - Operation Linkages

Perhaps more important to the objectives of this review are the linkages between the research and operation communities. In recognition of apparent difficulties, it has been noted that from an operational standpoint, while fundamental research is important, by the time this research can be implemented operationally, the users' requirements may have changed.

Apparent incompatibility may arise from the fact that the researcher and operational user generally have different priorities for ice forecast information. Generally, a research model provides a tool for better understanding of the physical processes involved in a particular problem. For the operational user the process is likely secondary with the specific forecast conditions being of primary importance. In this respect, the operational user requires that information be provided to an acceptable level of accuracy and reliability. Since this may vary with the application, careful consideration needs to be given to operational requirements at the onset of model development.

Based on the oil and gas industry user survey (B. Wright, 1991, pers. comm.), operational users feel that most sea ice models have been designed as research tools

with operational requirements only being considered several steps later in the development
process. Discussion with several Canadian researchers acknowledge that state of the art model development is frequently oriented to research priorities and that ideally research and operational objectives should be pursued in parallel if possible.

Informal exchange frequently occurs on a personal level but this tends to be narrowly focused. For example, good "rapport" may be established between two individuals with the result that the operational needs of the one may be accommodated. Some users and researchers appear to have been more successful at this than others. For example, in examining ice-ocean interaction processes, P. Budgell (formerly at BIO) has developed and/or adopted a series of numerical models from several institutes and individuals [e.g. G. Mellor (Princeton Univ.); AES (Ice Centre); L. Smith (Univ. of Miami); J. Overland and C. Pease (NOAA)].

Other examples of this type of research-operation linkage included the following ongoing cooperative efforts between Ice Centre and BIO:

- development, implementation and testing of a coupled ice-barotropic ocean model; and

- general cooperation in the observation of oceanographic parameters (e.g. offshore Labrador) and transfer of information to the Ice Centre for ice forecast improvement (e.g. advection due to ocean currents).

Informal linkages may be forged between researchers and operational users as researchers pursue project funding from bodies such as the National Science and Engineering Research Council (NSERC). Demonstrated industry support for a research proposal may be important in the funding application process. At the same time the linkage fosters communication between the two groups that might not otherwise occur.

Other linkages exist in the form of joint committees and funding bodies. These include the PERD committee (Task 6.7) supporting this work. A subcommittee within this body, the Operational Ice Modelling Working Group was formed in 1987 to promote the transfer of existing research to AES, Ice Centre operations and to promote additional research in support of general operational requirements. Committee members are drawn from AES, BIO, IOS, NEB and industry, providing representation from both the operations and research communities. The working group meets regularly and has recently initiated a project to develop standardized model verification procedures and verification data sets for the Beaufort Sea and Labrador Sea/Grand Banks area.

Another linkage exists through the Environmental Studies Research Fund (ESRF). The

ESRF is supported through levies on the oil and gas industry and has a mandate to promote environmental research based on industry priorities. These are wide-ranging but have included several ice-related studies.

Few open forums exist in Canada whereby the research and operational ice communities can interact more widely. Conferences such as POAC are the exception. A useful venue of this type was the 1986 East Coast Sea Ice Workshop which included participants from both the operational and research communities. On a smaller scale, the Ice Community Newsletter is published quarterly and provides an information forum for industry, government and academic activity in the area of ice.

6.0 REVIEW SUMMARY

A state of the art review has been made of sea ice modelling in Canada considering both the operational requirements and use of ice forecast information, as well as research and development into the development of new models. The review has also considered international aspects of sea ice modelling which may have relevance to Canadian activities in this area.

An important objective of this review was to evaluate how operational needs are being met. In order to do this, user requirements were investigated. Users were categorized in three main groups: government, industry and regulatory agencies. It was demonstrated that requirements such as the types of ice information required, its accuracy, and the temporal and spatial scales are reflective of particular user applications. While users frequently have similar applications, there are situations where unique needs dictates that a single model will not produce results to everyone's satisfaction.

On the basis of a wide variety of applications and specific output requirements, sea ice models were reviewed. As part of the review, models were grouped as presently operational or research-oriented. Additionally, models were categorized into five types, reflecting general applications. The categories were: ice growth and decay, ice edge prediction, small-scale ice behaviour, regional models and large-scale climate/global models. Important peripheral research which has potential applications to model development work was also reviewed.

A final consideration of the review was the linkages that exist within the research community and between it and the operational users. Structured linkages are few, based on comments from people involved in the various aspects of sea ice modelling. Formal information exchange is most commonly through publication of results or through presentations at open forums. Between the operational and research communities, personal interaction appears to dominate as a linkage.

The intent of this document was to provide a state of the art review of sea ice modelling which could be used for the evaluation of future research efforts. In presenting the review, user requirements have been compared with existing operational models, existing research models and plans for future research work. This information combined with the description of peripheral research activities may be used to guide decision making, to ensure that operational needs are being considered as improvements are made to existing ice forecast capabilities.

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APPENDIX A

MODEL SUMMARY SHEETS

General Summary of Models Presented in APPENDIX A

Sea Ice Model	Type	Applicability	Users
AES - Freezing Degree Day Ice Thickness Model (Zubov method)	G	O	Fed. gov't (AES)
AES - Heat Budget Ice Thickness Prediction Model	G	O	Fed. gov't (AES)
AES - Ice Freeze-up Model (Billelo method)	G	O	Fed. gov't (AES)
AES - Freeze-up and Break-up Forecast (Analog Method)	G	O	Fed. gov't (AES)
Gabison/AES - Thermodynamic Ice Growth and Decay Model	G	R	Fed. gov't (AES)
Miller - Seasonal Sea Ice Growth Model	G	R	industry (Petro-Canada)
El-Tahan - Ice-Floe Drift Model	E	O	private firm
Pritchard - Ice Edge Model	E	O,R	univ./priv./indus. NPS/firms/ARCO
Mellor - MIZ Coupled Ice-Ocean Model	E	R	university (Princeton)
Amoco/Canmar Ice-Forecasting	S	O	industry
Kozo - Sea-Ice Movement Forecasting Model	S,R	O	university (USNA/Alaska)
AES - Regional Ice Model	R	O,R	Fed. gov't (AES)
Ikeda - Labrador Shelf Dynamic/ Thermodynamic Sea-Ice Model	R	R	Fed. gov't (BIO)
Ikeda - Coupled Ice-Ocean Model	R	R	Fed. gov't (BIO)
IOS - Beaufort Sea Ice-Ocean Model	R	R	Fed. gov't (IOS)
Waterloo - Short-Term Sea-Ice Motion Model	R,S	R	university (Waterloo)
NOARL - High-Resolution Sea-Ice Model (RPIPS-B MODEL)	R,E	O,R	U.S. gov't (NORDA)
Lemke - Ice/Ocean Model with Mixed Layer Pycnocline Model	R	R	univ. (German & U.S. affiliations)
Lu - Mesoscale Sea-Ice Model	R	R	Danish gov't (Dan. Hydr. Inst)
Omstedt - Coupled One-Dimensional Sea Ice-Ocean Model	R	R	Swedish gov't (SNSRC)
Houssais - Thermodynamic Coupled Ice-Mixed Layer Model	R	R	U.S. gov't (CRREL)
Overland & Pease - Coastal Sea-Ice/Barotropic Ocean Model	R	R	U.S. gov't (NOAA)
Seaconsult - Long Range Ice Prediction Model	R	O	Fed. gov't (AES)
Simple Steady-State Coupled Ice-Ocean Model	C	R	university (McGill)
Hibler Coupled Dynamic/Thermodynamic Model	C,R	R	U.S. gov't (CRREL)
Hibler & Bryan - Diagnostic Ice-Ocean Model	C	R	university (Dartmouth/Princ)
Flato & Hibler - Cavitating Fluid Sea Ice Dynamics Model	C,R	R	university (Dartmouth Col.)
Semtner - Dynamic/Thermodynamic Sea-Ice Model	C	R	U.S. gov't (NCAR)
Semtner - Arctic Sea Ice and Ocean Circulation	C	R	U.S. gov't (NCAR)
Parkinson/Washington - Large-scale Numerical Model of Sea-Ice	C	R	U.S. gov't (NCAR)
Walsh & Zwally - Dynamic/Thermodynamic Sea-Ice Model	C	R	univ./U.S. gov't (Illinois & NASA)
Riedlinger - Arctic One Dimensional Ice-Ocean Model	C	R	U.S. gov't (NORDA)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.

MODEL NAME:	AES - Freezing Degree Day Ice Thickness Prediction (Zubov method)

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	G
APPLICABILITY	O
MOMENTUM BALANCE	n/a
ENERGY BALANCE	- uses Zubov ice thickness model -calculate ice thickness on the basis of FDD accumulation and initial ice thickness
ICE RHEOLOGY	n/a
BOUNDARY CONDITIONS	n/a
FORMULATION	n/a
GRID RESOLUTION	n/a
TIME STEP	variable
# OF ICE TYPES	first year ice
MODEL INPUTS WIND CURRENT ICE COMMENTS	-Freezing degree day; initial ice thickness.
OUTPUTS	T
GEOGRAPHICAL AREA TESTED	Great Lakes
ADDITIONAL COMMENTS	-does not take into account snow cover; -forecast ice growth based on forecast FDD accumulator.
SOURCE	AES (personal communication)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME: AES - Heat Budget Ice Thickness Prediction Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	G
APPLICABILITY	O
MOMENTUM BALANCE	n/a - Erian Petrie (BIO) has looked at advection effects on ice transport and water cooling.
ENERGY BALANCE	- freeze-up dates calculated using Laevusta heat budget equations
ICE RHEOLOGY	n/a
BOUNDARY CONDITIONS	n/a
FORMULATION	n/a
GRID RESOLUTION	n/a
TIME STEP	variable
# OF ICE TYPES	first year ice
MODEL INPUTS WIND CURRENT ICE COMMENTS	- observed, predicted wind speed -also cloud cover, air temperature, water temperature profile; -salinity profile
OUTPUTS	T
GEOGRAPHICAL AREA TESTED	Gulf of St. Lawrence; Beaufort Sea (using CTD profiles from dull ships).
ADDITIONAL COMMENTS	- model run for 8 stations in the Gulf of St. Lawrence; - XBT's deployed in Nov. & Dec. for temperature profiles; - BIO conducts late Nov. to collect CTD profiles for the same sites.
SOURCE	AES (personal communications)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	AES - Ice Freeze-up Model (Billelo method)

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	G
APPLICABILITY	O
MOMENTUM BALANCE	n/a
ENERGY BALANCE	-considers the decay of water temperature as function of a simple site specific constant.
ICE RHEOLOGY	n/a
BOUNDARY CONDITIONS	n/a
FORMULATION	- correlates accumulation of weighted daily mean air temperatures with freeze-up dates
GRID RESOLUTION	N - site specific calculation
TIME STEP	daily
# OF ICE TYPES	first year ice
MODEL INPUTS WIND CURRENT ICE COMMENTS	-requires daily air temperature.
OUTPUTS	predicts freeze-up date
GEOGRAPHICAL AREA TESTED	Great Lakes; St. Lawrence River.
ADDITIONAL COMMENTS	-after Billelo (1964); -predicts date or range of dates for localized freeze-up.
SOURCE	Lapp (1988)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_s) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; ;(C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature;(S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME: AES - Analog Method for Freeze-up and Break-up

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	G
APPLICABILITY	O
MOMENTUM BALANCE	n/a
ENERGY BALANCE	- relates historical freeze-up dates with freezing degree day accumulations, mean monthly air temperatures, sea surface temperature and existing ice conditions
ICE RHEOLOGY	n/a
BOUNDARY CONDITIONS	n/a
FORMULATION	n/a
GRID RESOLUTION	site specific calculation
TIME STEP	daily
# OF ICE TYPES	first year ice
MODEL INPUTS WIND CURRENT ICE COMMENTS	- mean monthly temperatures, sea surface temperature -30 and 90 day temperature anomaly progs aid in final selection of optimum analog
OUTPUTS	- predicts freeze-up date
GEOGRAPHICAL AREA TESTED	
ADDITIONAL COMMENTS	
SOURCE	Lapp (1988)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_d) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME: Gabison/AES - Thermodynamic Ice Growth and Decay Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	G
APPLICABILITY	R
MOMENTUM BALANCE	n/a
ENERGY BALANCE	-coupled to a one dimensional mixed layer model; -simulates mixing due to convection, turbulence & tidal effects.
ICE RHEOLOGY	n/a
BOUNDARY CONDITIONS	$T = T_w$ at ice-water interface
FORMULATION	-finite difference derivation (Crank-Nicholson implicit finite difference scheme to maintain numerical stability over long periods).
GRID RESOLUTION	n/a
TIME STEP	
# OF ICE TYPES	models F4 ice growth
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_s modeled -atmospheric forcing:- effects of cloud cover, air temperature, dew point; -snow cover (fixed depth, linear temperature profile).
OUTPUTS	-ice growth; sensible/latent heat flux; long-wave thermal emission; conductive heat flux.
GEOGRAPHICAL AREA	Three sites in the Arctic : Frobisher Bay, Cambridge Bay, Alert.
ADDITIONAL COMMENTS	-ocean-mixed layer - 12 levels (5m apart); -modification of model developed by Maykut and Untersteiner (1971); -prediction of localized ice growth and decay.
SOURCE	Gabison (1987)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_o) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME: Miller - Seasonal Sea Ice Growth Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	G
APPLICABILITY	R
MOMENTUM BALANCE	n/a
ENERGY BALANCE	-model based on an energy conservation approach using synoptic-scale climatic variability and site characteristics.
ICE RHEOLOGY	n/a
BOUNDARY CONDITIONS	
FORMULATION	explicit finite difference solution
GRID RESOLUTION	n/a
TIME STEP	daily
# OF ICE TYPES	first year ice growth
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_s initial thickness -air temperature; solar radiation; snowfall; mean station pressure; ocean salinity (monthly values interpolated for daily values); snowfall ocean in two snowfalls per month.
OUTPUTS	
GEOGRAPHICAL AREA TESTED	Eureka, Frobisher Bay, Resolute
ADDITIONAL COMMENTS	-sensitivity analysis to variations in temperature, solar radiation, snow depth, snow density, wind speed; -localized ice growth and decay prediction.
SOURCE	Miller (1986), Miller (1981b)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (N) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	El-Tahan - Ice-Floe Drift Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	E
APPLICABILITY	O
MOMENTUM BALANCE	-water/ice & air/ice drag coefficients; Coriolis force; ocean tilt; wind speed; water & air densities; ice floe velocity; surface current velocity; ice thickness.
ENERGY BALANCE	
ICE RHEOLOGY	F
BOUNDARY CONDITIONS	
FORMULATION	
GRID RESOLUTION	
TIME STEP	-wind record is composed of a series of 8 step functions with equal intervals of 6 hrs each.
# OF ICE TYPES	
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_g & W_s C_x I_v -Coriolis force & ocean surface slope considered
OUTPUTS	I_v & C_p
GEOGRAPHICAL AREA TESTED	Grand Banks
ADDITIONAL COMMENTS	-predicts short-term (1-2 day) drift of the ice-edge; -thermodynamic aspect (ice growth/melt) of the sea-ice modelling is ignored; -input data from drilling operations, vessel & air surveillance.
SOURCE	El-Tahan & Warbanski (1987)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_x) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME: Pritchard - Ice Edge Forecast Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	E
APPLICABILITY	O & R
MOMENTUM BALANCE	-inertia included to describe tidal & inertial behavior.
ENERGY BALANCE	-coupled 3-D ocean model; -radiative components; oceanic & salt fluxes included.
ICE RHEOLOGY	-E/P; constitutive law has 4 elements: 1) yield constraint; 2) flow rule; 3) elastic response; 4) kinematic relationship.
BOUNDARY CONDITIONS	-far-field boundary conditions: traction at ice edge is zero; along coastlines ice velocity is zero; -initial 2-layer profile: sea surface temperatures measured from imagery.
FORMULATION	choice of Lagrangian &/or Eulerian
GRID RESOLUTION	-defined by ice-edge motion & ice grid motion; -50 km; 5km near the edge.
TIME STEP	-ice model: integrated explicitly using a leap-frog scheme with time step of 10 min for 50km grid cells; -ocean model: variables on the Arakawa B grid with alternating-direction implicit scheme (time step of 3hrs); -both models are coupled explicitly with known state of ice.
# OF ICE TYPES	first year ice
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_g & W_s C_x I_v -initial conditions measured T & concentrations; -fluxes of heat & salt & water stress are linear; -atmospheric forcing including non-linear wind stress & barometric pressure & used until velocities reached quasi-steady state; mixed layer depth for open water; SST & salinity for pack ice.
OUTPUTS	I_c ; S_c ; SST; S; I_v
GEOGRAPHICAL AREA TESTED	Bering Sea
ADDITIONAL COMMENTS	-provide 5-7 day forecasts; -used NCAR input data in validation; -simulation of observed ice-edge from 1983 MIZEX-west & other drilling info (5 km/d accuracy); -can make a real-time ice forecasting within an hour.
SOURCE	Pritchard et al.(1990); Pritchard (1988).

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_s) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Mellor - MIZ Coupled Ice-Ocean Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	E
APPLICABILITY	R
MOMENTUM BALANCE	-air/ice & air/water drag coefficients set according to MIZ.
ENERGY BALANCE	-double diffusion exchange of heat/salt; careful treatment of turbulent exchange between ice/water interface.
ICE RHEOLOGY	V/P
BOUNDARY CONDITIONS	-surface boundary for ocean: Neumann-Dirichlet boundary condition for velocity (M & K, 1989); -assume a given influx of ice; integrated from arbitrary homogeneous initial conditions (K & M, 1989); -an added ice-ocean interface (H & M, 1990).
FORMULATION	Eulerian (same as RIM)
GRID RESOLUTION	45 x 22 km 7.5 km
TIME STEP	1.5 hr with a 4-day period
# OF ICE TYPES	-3 layers: 1)snow/ice surface; 2) ice internal; 3) ice/ocean.
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_s C_m(2-D) -water properties, salinity & temperature for outershelf & shelf break.
OUTPUTS	$C_T C_p I_v$
GEOGRAPHICAL AREA TESTED	-Bering Sea (ocean model); -simulate MIZEX West (1983 period).
ADDITIONAL COMMENTS	-finite difference formulation to solve equation; -usage is geared towards understanding MIZ variability; -ice rheology is important under on-ice conditions; -includes barotropic tides; -Wind velocity is assumed uniform across MIZ; -applied to 100yrs of simulated arctic ice-cover variations.
SOURCE	Kantha & Mellor (1989); Hakkinen & Mellor (1990); Mellor & Kantha (1989)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_d) - Modelled Current; (I_v) - Ice Velocity; (I_t) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_T) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Amoco/Canmar Ice-Forecasting

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	S
APPLICABILITY	O -2 forecasting systems are used: 1) simple wind driven model & a viable measured data model; 2) analogue model of measured ice movement & recorded wind velocities.
MOMENTUM BALANCE	
ENERGY BALANCE	
ICE RHEOLOGY	
BOUNDARY CONDITIONS	
FORMULATION	
GRID RESOLUTION	8 x 8 km & 8 x 12 km
TIME STEP	
# OF ICE TYPES	-air & vessel surveillance; SAR imagery input.
MODEL INPUTS WIND CURRENT ICE COMMENTS	
OUTPUTS	near-real time forecasting; wind velocity & forecasting; I_C
GEOGRAPHICAL AREA TESTED	southern Beaufort Sea
ADDITIONAL COMMENTS	-monitor ice movements over the past 12-24hrs; -measure environmental parameters & ocean current; -ice thickness, wind forecasts & ocean current velocities of prime importance.
SOURCE	Steen & Trobak (1986)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Kozo - Sea-Ice Movement Forecasting Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	S & R
APPLICABILITY	O
MOMENTUM BALANCE	-wind/water stress components
ENERGY BALANCE	
ICE RHEOLOGY	
BOUNDARY CONDITIONS	
FORMULATION	
GRID RESOLUTION	5 x 5 km
TIME STEP	
# OF ICE TYPES	
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_g C_x -surface atmospheric pressure & temperature used to compute W_g
OUTPUTS	I_v & W_g
GEOGRAPHICAL AREA TESTED	Bering Strait
ADDITIONAL COMMENTS	-sea ice movement derived from 11yrs of NOAA 3-8 VHRR; -developed an empirical 12hr advance forecast sea ice movement model with all-weather capabilities; -designed to identify ice movement & ice distribution; -85% accuracy.
SOURCE	Kozo et al. (1987)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME: AES - Regional Ice Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	R
APPLICABILITY	O & R
MOMENTUM BALANCE	-Coriolis force; sea surface slope; internal ice stress, formation & melt destruction; air/ice & ice/water drag coefficients; etc.
ENERGY BALANCE	-air temperature; water temperature.
ICE RHEOLOGY	V & P
BOUNDARY CONDITIONS	ice velocity = 0; internal stress = 0
FORMULATION	Eulerian
GRID RESOLUTION	42.3 km per 1 hour or adjustable
TIME STEP	
# OF ICE TYPES	10
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_s C_x I_c -alongshore wind stress & atmospheric cooling; -daily atmospheric observations are used as forcing.
OUTPUTS	C_p ; ice strength; C_T ; T; R
GEOGRAPHICAL AREA TESTED	Labrador Sea; Beaufort Sea; Grand Banks; Gulf of St. Lawrence.
ADDITIONAL COMMENTS	-prediction of short-term ice fluctuations; -will be coupled with an ocean circulation model.
SOURCE	Intera Tech. Ltd (1987); Nerella et al. (1988).

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Ikeda - Labrador Shelf Dynamic/Thermodynamic Sea Ice Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	R
APPLICABILITY	R
MOMENTUM BALANCE	-air & water stresses; Coriolis force; sea surface slope; internal ice stress; air/ice & ice/water drag coefficients.
ENERGY BALANCE	-radiative components; wind; air temperature; dew point; cloudiness.
ICE RHEOLOGY	P with modified V
BOUNDARY CONDITIONS	-dynamic shelf flow model; 3 boundaries: northern, offshore & southern.
FORMULATION	Eulerian
GRID RESOLUTION	25 x 50 km
TIME STEP	0.25 day
# OF ICE TYPES	- 2 level formulation of ice thickness
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_g C_x I_c -mainly atmospheric forcing; -Hibler's model tuned with an upward heat flux from the lower ocean to the surface mixed layer.
OUTPUTS	I_c is simulated to give accumulated ice.
GEOGRAPHICAL AREA TESTED	Labrador Shelf
ADDITIONAL COMMENTS	-simulated fluctuations in annual sea-ice cover; -interannual variability is produced by thermodynamics.
SOURCE	Ikeda et al. (1988)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_s) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Ikeda - Coupled Ice-Ocean Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	R
APPLICABILITY	R
MOMENTUM BALANCE	-wind stress; ice/water stress; Coriolis force; pressure gradient; internal ice stress gradient.
ENERGY BALANCE	-same as Ikeda et al. (1988)
ICE RHEOLOGY	V; V/P constitutive law
BOUNDARY CONDITIONS	-dynamic shelf flow model; 3 boundaries: northern, offshore & southern are open; constant ice thickness; zero heat flux thru ice.
FORMULATION	Eulerian
GRID RESOLUTION	25 x 50 km
TIME STEP	
# OF ICE TYPES	-2 layer ice model: -75 m thick surface mixed layer (Y & I, 1990); -30 m thick surface mixed layer (I, 1989b).
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_g; W_s C_m I_c -alongshore wind stress & atmospheric cooling; -daily atmospheric observations are used as forcing.
OUTPUTS	I_v & C_T
GEOGRAPHICAL AREA TESTED	east coast of North America & Greenland.
ADDITIONAL COMMENTS	-simulate growth phase of ice & the evolution of the upper ocean temperature & salinity; -LIMEX '87 & '89 data provided verification (I, 1989b).
SOURCE	Ikeda (1988; 1989a & b); Yao & Ikeda (1990)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_d) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_T) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	IOS - Beaufort Sea Ice-Ocean Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	R
APPLICABILITY	R
MOMENTUM BALANCE	
ENERGY BALANCE	-later version coupled with 3-D isopycnal coordinate ocean circulation model (4 active layers); -also coupled to curvilinear coordinate multi-level 3-D model developed by Mellor.
ICE RHEOLOGY	VP, F, modified P (Reinn-Rivlin approach O & P, 1988)
BOUNDARY CONDITIONS	-requires rectangular domain for equation solver; -cannot use irregular lateral boundaries; -uses periodic boundary conditions in one direction.
FORMULATION	
GRID RESOLUTION	18 km
TIME STEP	
# OF ICE TYPES	
MODEL INPUTS WIND CURRENT ICE COMMENTS	
OUTPUTS	I_V ; T; oceanographic parameters
GEOGRAPHICAL AREA TESTED	Beaufort Sea
ADDITIONAL COMMENTS	-uses periodic boundary conditions; -computational problems.
SOURCE	Smith et al. (1988); PERD 6.7 (minutes).

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_s) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME: Waterloo - Short-Term Sea-Ice Motion Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	R
APPLICABILITY	R
MOMENTUM BALANCE	-ice velocity; Coriolis force; geostrophic ocean current; surface winds; ice strength; air/ice & ice/water drag coefficients; sea surface tilt.
ENERGY BALANCE	
ICE RHEOLOGY	V, F & V/P
BOUNDARY CONDITIONS	-3 types: 1) Neumann; 2) Dirichlet; 3) mixed.
FORMULATION	-finite element method based on the Galerkin method of weighted residuals; -choice of Eulerian <u>or</u> Lagrangian.
GRID RESOLUTION	40 x 40 km
TIME STEP	-leap-frog time step using a Newton-Rapheon scheme.
# OF ICE TYPES	-2 type: 1) multicategory approach & determines ice strength; 2) Hibler's 2-level approach (thick & thin). -SLAR imagery input.
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_g ; W_s C_x I_v -very detailed components.
OUTPUTS	I_v ; C_T ; T
GEOGRAPHICAL AREA TESTED	southern Beaufort Sea
ADDITIONAL COMMENTS	-model applied to a 4-day ice motion period (1988); -determined sensitivity & uncertainty analysis of results from such a model.
SOURCE	Thomson & Sykes (1990); Thomson et al. (1988)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_d) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_T) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	NOARL - High-Resolution Sea-Ice Model (RPIPS-B MODEL)

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	R & E
APPLICABILITY	O & R
MOMENTUM BALANCE	-air/water stresses; Coriolis force; ocean tilt; internal stresses.
ENERGY BALANCE	-air/ice/ocean heat budget; surface/ice temperature.
ICE RHEOLOGY	V/P
BOUNDARY CONDITIONS	-inflow boundary conditions; land boundaries are solid walls; open boundaries are either ice outflow or ice inflow/outflow boundaries.
FORMULATION	Eulerian
GRID RESOLUTION	- 25 km (P & P, 1990); 127 km (P et al., 1986)
TIME STEP	- 2 levels: 1) thick ice (7 levels); 2) thin ice.
# OF ICE TYPES	
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_g C_x I_c -NOGAPS model provides six atmospheric forcing fields: (1) surface air temp.; (2) sensible heat flux; (3) total heat; (4) incoming solar radiation; (5) surface pressure; (6) surface vapor pressure; -Hibler/Bryan coupled ice/ocean model used as the ocean forcing; -climatological heat fluxes used.
OUTPUTS	T; I_v & I_c
GEOGRAPHICAL AREA TESTED	-Barents Sea & western part of the Kara Sea (P & P, 1990); -central Arctic, Barents Sea & Greenland/Norwegian Sea (P et al., 1986).
ADDITIONAL COMMENTS	-good agreement with 1983 & 1986 data between modeled & observed sea-ice characteristics; -tested in real-time operational environment; -results show a good estimate of the location of the ice-edge & a more detailed description of the movement of the ice around land boundaries; -RPIPS-B provides daily 120hr forecasts of ice drift, ice thickness & ice concentration.
SOURCE	Olaussen et al. (1988); Preller et al. (1986); Preller & Posey (1990).

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Lemke - Ice/Ocean Model with Mixed-Layer Pycnocline Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	R
APPLICABILITY	R -used to evaluate variability of ocean heat flux
MOMENTUM BALANCE	-two layer dynamic/thermodynamic sea ice model (Hibler model)
ENERGY BALANCE	-coupled mixed-layer pycnocline model (one dimensional); vertical oceanic heat flux no longer prescribed; -prognostic calculation of mixed layer depth; temperature; salinity; exponential shape of thermocline and halocline as a function of ice production and velocity.
ICE RHEOLOGY	VP
BOUNDARY CONDITIONS	-cyclic boundary conditions at the east-west boundaries
FORMULATION	Eulerian
GRID RESOLUTION	$2^{o} \times 2^{o}$ $2.5^{o} \times 5^{o}$ (Stossel et al. 1990)
TIME STEP	-one day (Owens and Lemke, 1990)
# OF ICE TYPES	-two thicknesses
MODEL INPUTS WIND CURRENT ICE COMMENTS	 -daily average; -C_g (Geostrophic current calculated from dynamic topography); -initialized with 10/10 cover, 2m thick ice cover; -initial oceanic heat flux of 2 W/m^2; -integrated for 4 years before starting analysis; -monthly input data interpolated to daily values; -Owens and Lemke (1990): -snow depth included (assume linear temperature gradient through snow and ice).
OUTPUTS	I_v ; C_T ; T
GEOGRAPHICAL AREA TESTED	Weddell Sea & ice cover surrounding Antarctica
ADDITIONAL COMMENTS	-sensitivity studies done; -Owens and Lemke (1990): -sensitivity to 1) the inclusion of a snow cover and 2)different ice rheologies; -Stossel et al. (1990) -sensitivity to 1) fixed mixed layer; 2) no snow cover; 3) higher ice strength; 4) slower lead closing; 5) no advection; 6) no ocean currents and 7) alternative, wind, temperature, precipitation forcing.
SOURCE	Lemke et al.(1990); Owens & Lemke (1990); Stossel et al. (1990)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_T) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Lu - Mesoscale Sea Ice Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	R
APPLICABILITY	R
MOMENTUM BALANCE	-integrated with respect to the vertical direction
ENERGY BALANCE	-ice growth/decay on the basis of heat flux balance
ICE RHEOLOGY	F; VP with floe collision in MIZ
BOUNDARY CONDITIONS	-require definition of thickness; concentration and velocity. -moving boundaries between MIZ and central pack ice and at ice edge result in substantial savings in computational time.
FORMULATION	Eulerian
GRID RESOLUTION	10 km
TIME STEP	2 to 12 hrs
# OF ICE TYPES	- three level ice thickness distribution
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_{10}(thermodynamics) & W_g (dynamics) C_x? I_v , I_c , 3 thicknesses
OUTPUTS	C_T ; T; C_p ; V; Ice Edge (est. as 1/10 concentration)
GEOGRAPHICAL AREA TESTED	East Greenland Sea (concentration evaluated against remotely sensed ice cover)
ADDITIONAL COMMENTS	-potential application for sea ice forecasting in subpolar regions
SOURCE	Lu, Larsen & Tryde (1989)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_a) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_T) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Omstedt - Coupled One-Dimensional Sea Ice-Ocean Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	R
APPLICABILITY	R
MOMENTUM BALANCE	
ENERGY BALANCE	-fluxes due to sensible; latent heat and net long-wave/short-wave radiation considered; - 1-D ocean model for oceanic heat flux.
ICE RHEOLOGY	
BOUNDARY CONDITIONS	implicit finite difference
FORMULATION	
GRID RESOLUTION	
TIME STEP	daily
# OF ICE TYPES	one
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_{10} -air temperature, relative humidity, surface water temperature.
OUTPUTS	T ; CT ; I_V
GEOGRAPHICAL AREA TESTED	Bothnian Bay
ADDITIONAL COMMENTS	-verification indicates need for 2 or 3-D ocean model; -sensitivity work done; -evaluated for semi-enclosed basin (Bothnian Bay).
SOURCE	Omstedt (1989; 1990)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_d) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Houssais - Thermodynamic Coupled Ice-Mixed Layer Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	R
APPLICABILITY	R
MOMENTUM BALANCE	-spatially & temporally uniform; - 3-D primitive equation model that calculates the ocean velocity field & its contribution to the time evolution of temperature-salinity distribution; & describes the pycnocline characteristics at the mixed layer base.
ENERGY BALANCE	-oceanic heat flux; surface fluxes; radiative components.
ICE RHEOLOGY	
BOUNDARY CONDITIONS	-atmospheric & oceanic boundary layers
FORMULATION	Eulerian
GRID RESOLUTION	15 km
TIME STEP	-integrated explicitly using a leap-frog scheme with an Asselin filter at each 12 hr time step over 5 yrs.
# OF ICE TYPES	one
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_s C_m I_c -temperature & salinity profiles included in the mixed layer model.
OUTPUTS	I_v ; C_T ; T ; S ; S_c ; SST
GEOGRAPHICAL AREA TESTED	Greenland Sea; subarctic conditions
ADDITIONAL COMMENTS	-designed to study the seasonal cycle of ice-ocean interactions; -predicts the rate of penetrative convection within the water column as a result of surface buoyancy flux & mechanical energy input.
SOURCE	Houssais (1986)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_T) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Overland & Pease - Coastal Sea-Ice/Barotropic Ocean Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	R
APPLICABILITY	R
MOMENTUM BALANCE	-air/ice; air/water; ice/water & water/bottom drag coefficients; Coriolis force; air/ice/water densities; shear viscosity; ice strength; sea surface tilt.
ENERGY BALANCE	
ICE RHEOLOGY	modified P (constitutive law has 6 elements)
BOUNDARY CONDITIONS	-top to bottom; surface current, slope current & bottom current; wind speed & direction; ice thickness & compactness.
FORMULATION	-explicit finite difference methods on a staggered grid
GRID RESOLUTION	1 km
TIME STEP	15 to 30 s
# OF ICE TYPES	0.8 m initial ice thickness
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_g & W_s C_x (tidal) I_c
OUTPUTS	I_v & T
GEOGRAPHICAL AREA TESTED	Alaskan coast
ADDITIONAL COMMENTS	-used in alongshore wind cases & onshore wind cases.
SOURCE	Overland & Pease (1988)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Seaconsult - Long Range Sea Ice Prediction Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	R
APPLICABILITY	O
MOMENTUM BALANCE	
ENERGY BALANCE	
ICE RHEOLOGY	
BOUNDARY CONDITIONS	
FORMULATION	-statistical analysis using eigen function; -coefficients from empirical functions allow to indentify analogue years.
GRID RESOLUTION	-regional forecast centred over Labrador
TIME STEP	
# OF ICE TYPES	
MODEL INPUTS WIND CURRENT ICE COMMENTS	 C_T -sea level pressure (upper level, 500 & 700 mb geopotential height); atmospheric thickness parameter; surface air temperature; relative humidity.
OUTPUTS	-areal extent; volume of ice present.
GEOGRAPHICAL AREA TESTED	Grand Banks, Labrador, Gulf of St. Lawrence
ADDITIONAL COMMENTS	-requires 4 months of weather data;
SOURCE	L. Davidson (1991, pers. comm.)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.

Applicability: (O) - Operational; (R) - Research.

Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.

Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.

Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Simple Steady-State Coupled Ice-Ocean model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	C
APPLICABILITY	R
MOMENTUM BALANCE	-ice/water & air/ice drag; Coriolis force.
ENERGY BALANCE	-ice temperature; ocean temperature; air temperature; specific heat capacity of sea water; eddy diffusion coefficient for heat.
ICE RHEOLOGY	
BOUNDARY CONDITIONS	-western boundaries: Stommel-type frictional boundary current (Willmott & M, 1989); -temperature boundary conditions; 3 boundaries: northern, southern & eastern (Wood & M, 1989).
FORMULATION	finite element; Eulerian
GRID RESOLUTION	20 x 20 km (Wood & M, 1989); 30 km (Willmott & M, 1989).
TIME STEP	
# OF ICE TYPES	stationary slab
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_s C_m I_c -easterly flow forced by topography.
OUTPUTS	I_e ; C_T ; SST ; T
GEOGRAPHICAL AREA TESTED	Greenland/Norwegian Sea; Labrador Sea & Davis Strait.
ADDITIONAL COMMENTS	-determines ice-edge position; -comparison of observed ice & ocean temperature data; -purpose of evaluating climate change.
SOURCE	Willmott & Mysak (1989); Wood & Mysak (1989)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_d) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_T) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Hibler Coupled Dynamic/Thermodynamic Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	C & R
APPLICABILITY	R
MOMENTUM BALANCE	-momentum balance considering air stress; water stress; coriolis force; internal ice stress; inertial forces and ocean tilt.
ENERGY BALANCE	-incorporates thermodynamic component to model ice thickness and increase in concentration as a result of ice growth; -initially used seasonal growth rate (constant value for entire Arctic) ; -fixed depth ocean mixed layer; -Hibler (1985): -full heat budget added; conserve air-sea heat exchange; -no snow cover included; approximated through ice albedo adjustment; -lateral melting included; -Hibler (1986): -incorporated 14 level baroclinic ocean model.
ICE RHEOLOGY	- VP -Hibler (1985): -included ridge distribution process. -Hibler (1986): -non-linear plastic rheology; -two level ice thickness distribution.
BOUNDARY CONDITIONS	
FORMULATION	-Eulerian; finite difference solution; -staggered grids for concentration and ice velocity.
GRID RESOLUTION	125 km
TIME STEP	implicit
# OF ICE TYPES	two ice thicknesses
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_g (eight day average) Cg (calculated from dynamic topography) -model integrated for several years to reach cyclic equilibrium; -constant heat flux from depth.
OUTPUTS	V ; C_T ; C_P ; T (two levels; Hibler,1985 - multiple levels)
GEOGRAPHICAL AREA TESTED	Arctic Basin
ADDITIONAL COMMENTS	-first effort at linking dynamic and thermodynamic components
SOURCE	Hibler, W.D. (1979); Hibler, W.D. (1985); Hibler, W.D. (1986)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Hibler & Bryan - Diagnostic Ice-Ocean Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	C
APPLICABILITY	R - investigate effect of multilevel baroclinic ocean model on seasonal sea; O - Ice-ocean forecasting.
MOMENTUM BALANCE	-two level dynamic/thermodynamic (Hibler 1979) with multilevel baroclinic ocean model (Bryan 1969).
ENERGY BALANCE	-diagnostic approach uses available temp and salinity data to force these aspects of the ocean rather than fully model them : supplied by sea ice model; -heat flux from ocean model to sea ice model.
ICE RHEOLOGY	V/P
BOUNDARY CONDITIONS	-for ocean model: rigid walls along outer grid points, damped by 30-day temperature and salinity adjacent to open ocean.
FORMULATION	Eulerian
GRID RESOLUTION	160 km
TIME STEP	daily
# OF ICE TYPES	
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_s (daily from FFGE year December 1978 to Nov 1979) -air temperature, humidity (monthly); -mean annual observed ocean temperature and salinity used to damp ocean model below mixed layer.
OUTPUTS	T, I_v , ocean currents, air temperature, salinity
GEOGRAPHICAL AREA TESTED	Arctic Basin
ADDITIONAL COMMENTS	-investigate effect of multilevel baroclinic ocean model on seasonal sea; -operational ice-ocean forecasting.
SOURCE	Hibler & Bryan (1987); Hibler (1979,1986); Bryan (1969).

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME: Flato & Hibler - Cavitating Fluid Sea Ice Dynamics Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	C & R
APPLICABILITY	R
MOMENTUM BALANCE	-begins by calculating free drift velocity.
ENERGY BALANCE	-Flato & Hibler (1990): constant heat flux; no explicit inclusion of snow.
ICE RHEOLOGY	cavitating fluid
BOUNDARY CONDITIONS	-no slip later boundary conditions at land boundary; -free flow into Greenland/Norwegian Seas.
FORMULATION	
GRID RESOLUTION	160 km
TIME STEP	daily
# OF ICE TYPES	one
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_s -air temperature, dew point, radiation and internal heat flux.
OUTPUTS	I_u T
GEOGRAPHICAL AREA TESTED	Arctic Basin
ADDITIONAL COMMENTS	-cavitating fluid approach runs = 2X as fast as VP formulation; -lack of shear strength affects detail in thick/air pattern; -climate study models: MIZ response to synoptic-scale disturbance.
SOURCE	Flato & Hibler (1988; 1990)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_u) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_u) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Semtner - Dynamic/Thermodynamic Sea-Ice Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	C
APPLICABILITY	R
MOMENTUM BALANCE	-sea surface slope; ice/water stress; Coriolis force; internal ice strength. -Hibler's formulation.
ENERGY BALANCE	-surface heat budget; precipitation.
ICE RHEOLOGY	Bulk V
BOUNDARY CONDITIONS	-observed temperature & salinity are prescribed only at inflow boundaries.
FORMULATION	Eulerian (finite difference)
GRID RESOLUTION	110 km
TIME STEP	
# OF ICE TYPES	
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_g ; W_s C_m -driven by monthly atmospheric forcing, observed river runoff & inflow.
OUTPUTS	I_v ; C_T ; T ; SST ; S_c ; P
GEOGRAPHICAL AREA TESTED	entire Arctic Basin & Greenland Sea
ADDITIONAL COMMENTS	-3 layer thermodynamic model of snow covered sea-ice coupled to a multi-level primitive equation ocean model; -the multi-level ocean model uses up to 13 levels in the vertical to resolve bathymetric variations; -examined the effects of Soviet river diversions & of CO_2-induced atmospheric temperature increases; -model simulations for a 20yr quasi-equilibrium run.
SOURCE	Semtner (1976; 1986)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_T) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Semtner - Arctic Sea Ice and Ocean Circulation

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	C
APPLICABILITY	R
MOMENTUM BALANCE	-as per Hibler (1979)
ENERGY BALANCE	-ocean model (13 levels) driven by prescribed inflow
ICE RHEOLOGY	bulk viscosity
BOUNDARY CONDITIONS	-water temperature/salinitypresented at inflow boundaries
FORMULATION	explicit time step
GRID RESOLUTION	110 km
TIME STEP	daily
# OF ICE TYPES	- 3 layer, snow covered ice surface
MODEL INPUTS WIND CURRENT ICE COMMENTS	 -inputs prescribed daily; -river inflow considered.
OUTPUTS	T ; C_T ; C_p ; SST ; S ; I_v ; S_c
GEOGRAPHICAL AREA TESTED	Arctic Basin
ADDITIONAL COMMENTS	-model optimized for running on a CRA4-1A; -ocean circulation and climate modelling.
SOURCE	Semtner (1987)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_T) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME: Parkinson & Washington - Large-scale Numerical Model of Sea-Ice

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	C
APPLICABILITY	R
MOMENTUM BALANCE	-wind & water stress; Coriolis force; sea surface tilt; internal ice resistance.
ENERGY BALANCE	-heat budget components; thermal conductivities of snow & ice.
ICE RHEOLOGY	E/P
BOUNDARY CONDITIONS	-continental boundaries
FORMULATION	Lagrangian
GRID RESOLUTION	-211.06 km at the poles to 181.006 km at the farthest edge of the north polar region and to 173.844 km at the farthest edge of the southern polar region.
TIME STEP	-mid-month
# OF ICE TYPES	-ice with snow cover; -ice with no snow cover.
MODEL INPUTS WIND CURRENT ICE COMMENTS	 W_g I_v -mean monthly atmospheric forcing; temperature & dew point are also input data.
OUTPUTS	C_T ; C_p ; T
GEOGRAPHICAL AREA TESTED	-northern & southern hemispheres
ADDITIONAL COMMENTS	-produced reasonable yearly cycle of sea ice thickness & extent in both the Arctic and Antarctic.
SOURCE	Parkinson & Washington (1979)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_T) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME: Walsh & Zwally - Dynamic/Thermodynamic Sea-Ice Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	C
APPLICABILITY	R
MOMENTUM BALANCE	-same as Ikeda's original sea-ice model.
ENERGY BALANCE	-heat budget components.
ICE RHEOLOGY	V/P
BOUNDARY CONDITIONS	-ice velocity vanishes at the coastline; thickness & compactness vanishes at the open boundaries.
FORMULATION	Eulerian
GRID RESOLUTION	222 km
TIME STEP	1-day
# OF ICE TYPES	first year ice and multiyear ice
MODEL INPUTS WIND CURRENT ICE COMMENTS	 C_g (Geostrophic) -monthly temperatures & daily snowfall included; daily sea level pressure.
OUTPUTS	I_v; C_T P & T
GEOGRAPHICAL AREA TESTED	Arctic Basin
ADDITIONAL COMMENTS	-includes a distinction between multiyear & 1st year ice; -compared simulated & satellite-derived data (SSMR) data for 1979-85.
SOURCE	Walsh & Zwally (1990); Zwally & Walsh (1987)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_a) - Mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_T) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

MODEL NAME:	Riedlinger - Arctic One Dimensional Ice-Ocean Model

MODEL CHARACTERISTICS	MODEL DESCRIPTION
TYPE	C
APPLICABILITY	R
MOMENTUM BALANCE	-ignore ice stress (neglects convergent & divergent motion).
ENERGY BALANCE	-utilizes Semtner (1976) operational; -layer thermodynamic model containing prognostic snow thickness, ice thickness & surface; -coupled to a mixed layer ocean model Mellor & Yamada (1974) 17 levels for temperature, salinity, density & velocity.
ICE RHEOLOGY	
BOUNDARY CONDITIONS	various
FORMULATION	finite difference solution for ice momentum
GRID RESOLUTION	
TIME STEP	6-8 hrs
# OF ICE TYPES	
MODEL INPUTS WIND CURRENT ICE COMMENTS	 monthly winds -mean monthly short/long wave radiation, sensible/latent heat, albedo, snowfall rate, ocean temperature & salinity initialized with profiles from a single location.
OUTPUTS	T; S; snow cover; water temperature; heat flux; water velocity
GEOGRAPHICAL AREA TESTED	Arctic Basin
ADDITIONAL COMMENTS	-climatological studies of the Arctic ice cap.
SOURCE	Riedlinger et al. (1990); Semtner (1976); Mellor and Yamada (1979)

Type: (E) - Ice Edge; (G) - Ice Growth; (R) - Regional; (S) - Small-scale; (C) - Climate.
Applicability: (O) - Operational; (R) - Research.
Ice Rheology: (V) - Viscous; (P) - Plastic; (E) - Elastic; (F) - Free Drift.
Model Inputs: (W_g) - Geostrophic Wind; (W_s) - Surface Wind; (C_m) - mean Current; (C_m) - Modelled Current; (I_v) - Ice Velocity; (I_c) - Ice Concentration; (T) - Ice Thickness.
Outputs: (I_v) - Ice Velocity; (C_t) - Total Concentration; (C_p) - Partial Concentration; (I_e) - Ice Edge; (P) - Pressure; (T) - Thickness; (R) - Roughness; (S) - Salinity; (SST) - Sea Surface Temperature; (S_c) - Surface Current; (W_g) Geostrophic Wind Velocity; (FL) - Floe Size.

APPENDIX B

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ANNEX B

Ocean Model Review

Status: Research, Development and Operational Use of Ocean Models

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SUMMARY

This study reviews oil spill trajectory models, current models, and wave models in order to provide a synopsis of present capabilities. The review focused on operational needs in Canada, the present status of operationally-oriented models, the ongoing and planned research, and the linkages between operations, research, and development.

Oil Spill Trajectory Models

Ten oil spill trajectory models were reviewed including three American models. The majority of the models use the same basic principles to predict advection and spreading. As well, the models tend to use various versions of Mackay's work to predict evaporation, dispersion, and emulsification. The operationally-oriented models differ in their treatment of input data, grid sizing, transportability to other regions, and the capability to predict evaporation, dispersion, emulsification, oil-in-ice spreading, and shoreline impact. The ability of oil spill trajectory models to use environmental data in the determination of the advecting surface currents exceeds the spatial and temporal resolution of the available climatic data.

The report summarizes the efforts of seven groups conducting research into oil spill modelling. Most of the on-going research efforts focus on improvements to fate and behaviour algorithms (evaporation, dispersion, emulsification, oil-in-ice). A low level of effort is devoted to improving environmental data or modelling of advection and spreading. Improved HF radar systems for measurement of surface currents may be able to provide real-time data to models in the near future.

Current Models

Oil spill trajectory models form one of the primary uses of operational current models. Other uses include search and rescue, fisheries management, oil and gas exploration, marine operations, iceberg drift models, and sea ice models.

Of the nine operationally-oriented current models identified in this review, eight fall into the class of barotropic models. The most sophisticated of these, the Operational Ocean Current Modelling System (OCS), still requires more development in order to implement it in an operational computer system, create a user-friendly interface, perform additional calibrations, and develop the flexibility to transport the model to other regions. BARO-2D and 2.5D-MULT have been developed for sea-ice models and iceberg drift analysis on the East coast. Two models are available for the Straits of Juan de Fuca and Georgia: TideView predicts tidal flow and DRIFTCALC predicts tidal and estuarine flow. A fourth model is part of a nation-wide search and rescue system called CANSARP. It consists of a database of non-tidal flow, calculated wind-forcing, and tidal models (for selected areas).

Current modelling research is aimed at the needs of fisheries research and oil spill trajectory modelling. Baroclinic models are being developed for the East and West Coast as well as the St. Lawrence River estuary.

Wave Models

Four wave models have been adopted for use in Canada. The Atmospheric Environment Service operates a first generation version of CSOWM (derived from Cardone's ODGP model) at the Canadian Meteorological Centre for the northwest Atlantic and northeast Pacific. PACWAV, a derivative of the ODGP with a unique interface for modifying input data, is run from the Pacific Weather Centre. Two other models reviewed, WAVAD and SPECREF, are proprietary. WAVAD is presently in commercial use on the East Coast

It appears that the accuracy of CSOWM and PACWAV in operational settings is still only comparable to simple wave nomograms used by experienced forecasters.

The report summarizes wave modelling research efforts at the various government reserch centres. These efforts cover a wide range of basic research such as data assimilation,

wind-wave coupling, and wave-current interaction as well as work to improve operational models.

Linkages

Linkages between research and operations were studied separately for each type of model. Four groups are involved in these linkages: researchers, developers, operators and users. In general the weakest link was found to be between users and the other three groups, as formal mechanisms for communication often stopped at the operator level.

Existing linkages between researchers and developers of oil spill trajectory models suffer from the process of remote communication through the published literature. This pattern may lead to omissions and errors in the way research algorithms are selected, incorporated, and applied in an operational model. Developers and operators have generally effective relationships in both industry and government.

The links between users and researchers of oil spill models is weak. The pro-active approach of the Technical Advisory Group steering the development of the "World Oil Spill Model" is an effective means of involving all parties in the creation of an operational model.

Researchers and developers of ocean current models have had close relationships during the development of operational models. A reduction in funding may affect this linkage in the future. Wave model development typically incorporates both the researcher and developer in the same organization.

Linkages in wave modelling are the strongest of the three types of models studied. Focused conferences, national and international committees bring researchers and developers together regularly. AES provides a focal point for Environment Canada research, development, and operations. They also have linkages to other Canadian researcher and to the international

wave modelling community. Again, the weakest link is between users (the oil and gas industry and mariners) and researchers.

The three types of models are also interlinked, primarily by the requirements for oil spill trajectory models to incorporate wave and current data.

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STUDY TEAM

The study team was composed of David Dickins, Ann Godon, and Martin Poulin of DF Dickins Associates Ltd. and Dan McGillivray of The MEP Company. To meet the timelines of other PERD projects, the majority of the study was conducted from mid-June to early August, 1991.

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1.0 INTRODUCTION

1.1 Scope of Work

The main objective of this review is to provide a synopsis of the operational capabilities and research activities in Canada concerning ocean modelling. Three types of models were reviewed: oil spill trajectory models, current models, and wave models. This study focused on identifying the following three items:

- the status of operational models, their characteristics, and user needs
- the research being conducted to improve the operational capabilities of the models, including the identification of peripheral research
- the linkages within and between the research and the operational communities

The available funding precluded a detailed evaluation of the models reviewed. The discussion in this report provides general information on model components and expected performance; the report is not intended to provide technical details concerning parameterization or physics. The important components of the models were reviewed for the purposes of providing an overall indication of capabilities, rather than to provide a basis for selecting operational models for given applications.

An evaluation of model validations was outside of the scope of work; references are provided should the reader wish to pursue this aspect further.

An extensive review of international modelling efforts was beyond the scope of this study. Section 5 discusses the linkages between selected international research groups and Canadian activities.

Given the tight schedule and budget, a decision was made at the outset to rely heavily on personal communications to collect source material. This approach provided a snapshot of on-going efforts that accurately reflected the current status of modelling in Canada. In contrast, information collected through the literature typically represents efforts conducted 1-3 years ago. Disadvantages of personal communication include a lack of referenced source material and the possibility of personal bias. Where possible, references to published literature are cited in this report, but in many cases publications are unavailable to cover the most recent programs.

This review was intended to produce a discussion paper. Readers will develop their own recommendations pertaining to future research and model development from the contents of this report. Conclusions are provided in Section 6 to highlight a number of the important findings.

1.2 Background

The Panel on Energy Research and Development (PERD) recognized a need to review the direction of research efforts required to provide effective oil spill trajectory, current, and wave models for operational use. Oil spill trajectory, current, and wave models were studied together in this project because of their natural interdependency. For example: oil spill trajectory models build on the predictions of wave and current models to determine the location and characteristics of the oil; current models are often required as input to wave models in areas of significant wave/current interaction and; waves contribute to longshore currents.

The study includes an examination of communications linkages between researchers, developers, operators, and users of models and their output products. The objective was to identify deficiencies in existing linkages in order to improve future funding mechanisms whereby research efforts can lead to more capable and effective operational products.

1.3 Definitions

For the purposes of this study, an "operational model" is defined as a numerical prediction system which uses forecasted or observed inputs (e.g., wind velocities) to compute output products (e.g., wave spectra, ocean currents, or oil slick trajectories) ahead of real-time. This study focuses on situations where model results are incorporated in forecasts or used as decision-making tools during emergencies (recognizing that some of the models discussed are also used to hindcast past events).

Models which are potentially operational (i.e., they have been designed and tested to run in a realistic operational setting, but are not in current regular use) have been defined in this study as "operationally-oriented" models.

The report makes frequent use of the terms "researchers", "developers", "users", and "operators". Researchers are considered as individuals who direct their efforts into modelling equations, numeric techniques or understanding of physical processes. Developers are concerned with the development of operationally-oriented models including decreasing numeric code complexity, and developing graphical displays and user-friendly interfaces. Developers may work closely with researchers to transform research models into operational models. Operators enter input data, run the model, and analyze output data to produce forecasts or hindcasts, but are not required to make decisions based on the model predictions. Users base decisions on the predictions of models and may not necessarily play a major part in the development or operation of models.

2.0 OIL SPILL TRAJECTORY MODELS

2.1 Operational Users

This section presents a number of the comments expressed by different users during the recent workshop held by Environment Canada to explore ways developing a more integrated national approach to the operational use of trajectory models (DF Dickins Assoc., 1991).

Operational oil spill trajectory models are used in Canada by spill response personnel in the petroleum industry, Environment Canada, and Coast Guard. Within the petroleum industry, response organizations such as the Beaufort Sea Coop and individual oil companies such as Esso Resources Canada Limited use spill trajectory models for contingency planning, emergency response, and training exercises. Conservation and Protection, Environment Canada uses spill trajectory models for similar purposes, but with more emphasis on emergency response. The Canadian Coast Guard uses trajectory models for strategic contingency planning and preparedness, but due to a lack of confidence in computer models, prefers to rely on aerial surveillance and tracking buoys during an actual spill response.

Trajectory model improvements most often requested by industry and government users are summarized in the following list (DF Dickins Assoc., 1991):

- real-time input of accurate environmental data
- flexibility (easily upgradeable with preferred sub-models, variable input data formats)
- user-friendliness
- improved fate and behaviour models

It is well recognized that the accuracy of trajectory models is highly dependent on the accuracy of the environmental input data (i.e., winds, currents). For emergency response situations, the difficulty lies in obtaining real-time, high resolution data that can be accessed quickly. For example, current information from the Department of Fisheries and Oceans

(DFO) is only conveniently accessed during regular office hours (exceptions are made depending on the emergency and availability of staff).

One technology which has the potential to supplement available current models is HF radar. HF radar systems or CODARs, can map surface currents using HF ground wave radar in real-time for site specific areas. This technology if employed operationally in coastal areas would reduce the dependency of model operators and users on ocean current models and databases.

The flexibility of any given model in an operational situation hinges on an ability to accept different types of input data, to model a variety of spill scenarios (including location), and to allow program code modifications. There is an ongoing need for models that can accept a variety of data input formats (environmental, shorelines etc.) depending on the availability of data. Future requirements include the development of models that will select particular fate sub-models depending on the scenario defined. A related complaint regarding a few of the present models is that they have been coded by scientists and not computer programmers; consequently, they are difficult to modify (M. Fingas in DF Dickins Assoc., 1991).

Models designed for emergency response must be user-friendly and operable with minimal training on the part of the users. Users need to be assured that operators (of trajectory models) are familiar with their limitations and deficiencies, and can properly interpret the results.

Users have indicated that the fate processes of emulsification and dispersion of oil in water must be more clearly defined and the model equations verified with laboratory and field data.

The verification of oil-in-ice model simulations is difficult due to the lack of field data concerning oil spreading in ice and oil advection in ice (Venkatesh et al., 1990a). Oil-in-ice scenarios are relevant to Arctic conditions in northern Canada and pack ice conditions in Eastern Canada.

The interaction of oil with the shoreline is a poorly understood process that should be investigated in future modelling efforts to properly predict and assess shoreline impact.

2.2 Operational Oil Spill Trajectory Models

2.2.1 Model Characteristics

Models have been developed for a variety of purposes: emergency response, contingency planning, training, and damage assessment. As a result different types of models and different modes of operation have evolved. Models are often defined as forecast, statistical (or stochastic), receptor, or hindcast.

Forecast models use forecast environmental data to predict oil trajectory and fate in real-time. During emergency response, models are usually used in a forecast mode to support clean-up decisions.

Statistical modes use data sets of wind statistics or a random selection of environmental conditions to run many trajectories from a known point or area. This mode is used for contingency planning in order to determine all the possible pathways of the oil and to determine the most likely trajectories (see Jayko and Spaulding, 1989).

If a particular site is extremely vulnerable to oil spills, a receptor analysis can be used to delineate the areas from which a spill source can impact the site within a given time period (see Galt and Payton, 1983).

The hindcast mode is primarily for model verification and spill reconstruction (see Galt et al., 1991). Observed winds and currents are input into the

hindcast model and the predicted behaviour compared to the observed behaviour.

The algorithms used to drive oil spill trajectory models may be broken into two components. The first component is the algorithm used to simulate the trajectory of the oil. Typically, the vector addition of ocean currents (residual, tidal, estuarine) and 3-4 % of the wind speed acting at 10-20° to the right of the wind provides the advecting current for the trajectory of oil parcels (or "spillets" as they are often termed). Thus, the trajectory is very sensitive to current and wind data. The format and nature of the required input parameters varies between models, but usually wind speed and direction can be entered as a function of both time and space. Current data is either embedded in the model or entered on a user-defined grid.

The second component is composed of the fate and behaviour algorithms that describe the spreading and weathering processes of oil on the water or on the shoreline. Almost all models use Fay's three regime equation (Fay, 1971) as a basis for calculating spreading. Models such as SLICK II also include a turbulent dispersion component which can be significantly affected by the value of the turbulent dispersion coefficient (Venkatesh, 1988).

The most important weathering processes are evaporation, dispersion, and emulsification which control the oil fate. The fate algorithms, model resolution, and division of the spill volume, along with the format of the inputs and outputs all contribute to the uniqueness of a particular model.

Most models incorporate some version of D. Mackay's work (Mackay et al., 1980a, 1980b; Mackay and Leinonen, 1977; Mackay and Zagorski, 1982; Stiver et al., 1989)) to describe the fate processes. Mackay's sub-models can differ dramatically from each other and must be chosen with care for the given application. For instance, Mackay's last published sub-model of evaporation is considered the most accurate, although earlier versions are often employed in trajectory models (Fingas in DF Dickins Assoc., 1991). Some oil spill

trajectory models incorporate sub-models of oil impacting with the shoreline, and other models incorporate oil motion in ice.

As output, most of the models produce screen displays and hardcopy maps of the trajectory and extent of the oil at user-defined time intervals. Depending on the fate algorithms used, tables of the oil mass balance at different stages of weathering or impact with a shoreline can also be produced.

Most operational models available at present run on micro computers (e.g., HP 9000 workstations) or personal computers. Execution of the program is usually within minutes.

2.2.2 Models Reviewed

Table 2.1 summarizes the state-of-the-art trajectory models (with incorporated fate models) that are intended for operational use in Canada's marine environment. Several of the more prominent models that are in use in the United States are also included.

The advection component is not specifically evaluated in Table 2.1; most models use a standard vector addition of wind driven surface currents, residual, and tidal currents (this approach is generally accepted as accurate if coastal or bathymetric effects are not significant - Spaulding, 1988). Some models apply another degree of sophistication, using various techniques to incorporate turbulent flow (i.e., SPILLSIM, see Hodgins et al., 1991).

Speed of execution, user-friendliness, and output quality are characteristics that are best evaluated first-hand. In lieu of the time and budget required to set-up demonstrations of each model, Table 2.1 relies on information supplied by model developers and operators and should be treated as a guide only in these areas.

The following paragraphs describe the unique characteristics of each model.

Table 2.1 Summary of Operationally-Oriented Oil Spill Trajectory Models

Note: The sources of evaporation, dispersion, and emulsification sub-models are listed by the primary researcher.

Model (Developer)	Primary Purpose (User)	Input Data	Input Format of Winds/Currents	Spreading	Evaporation Dispersion Emulsification	Computer System	Output (Resolution)
Beaufort Sea Co-op (ASA/Gulf)	emergency response, planning (Beaufort Sea Co-op)	wind, ice cover, current model (tidal & residual) oil properties, spill volume and type, location	uniform, time varying wind; 3-D hydrodynamic current model for area (spatial and time varying)	Fay's 3 regime	yes-Mackay yes-Mackay yes-Mackay	IBM 386	trajectory, extent, shoreline impact, mass balance (~ 300 m)
MIRG SL Ross (SL Ross ERL)	emergency response, dispersant use decisions (MIRG member companies)	winds, residual , currents, oil properties, spill location, shorelines	uniform, time varying wind; gridded currents	modified Fay with Mackay thick/thin	yes-Mackay yes-Audunson yes-Mackay	IBM PC	trajectory, extent, mass balance, ecological impact, (user-defined)
OILBRICE (Fleet Tech. AES, Crescent Consulting, Greenhorne & O'Mara)	emergency response, planning, (MMS, AES)	winds, residual and tidal currents, air temperature, ice cover, oil properties	dependent on trajectory model	empirical (in and out of ice)	no no no	IBM PC	trajectory, extent, thickness, mass balance in ice (1 km resolution)
Oil Spill Model Shell (ASA)	emergency response, planning, training (Esso Canada, CPA, Environment Canada)	wind spd/direct, residual currents, shorelines	uniform, time varying wind; gridded currents	Fay's 3 regime	yes-Mackay yes-Mackay yes-Mackay	IBM PC	trajectory, mass balance (default resolut. of 10 km)
OSP Model (ENSR)	emergency response, planning, permitting (Alaska Clean Seas)	winds, residual currents, waves, shoreline, ice cover,	uniform, time varying winds; gridded currents	Fay's 3 regime	yes-Mackay yes-Mackay yes-Mackay	Compaq 286	trajectory, mass balance (lat., long. grid-variable)

Model (Developer)	Primary Purpose (User)	Input Data	Input Format of Winds/Currents	Spreading	Evaporation Dispersion Emulsification	Computer System	Output (Resolution)
OSSM (NOAA)	emergency response, planning (NOAA)	winds, residual and tidal currents, shoreline, oil properties, location	gridded, time varying winds and currents or current model	turbulent diffusion	yes no no	IBM PC or Macintosh II series	trajectory, mass balance, shoreline impact (variable res.)
SCOOP (Esso & Scicon)	emergency response, planning (Esso)	wind, residual and tidal currents, shoreline, oil properties	interpolated time varying wind data; currents from atlas (gridded, time varying)	no model	yes-Mackay yes-Mackay no	SUN workstation	trajectory, thickness (hourly, variable res.)
SLICK II (AES)	emergency response, planning (AES)	winds, residual currents, tidal currents, oil surface tension, spill location, spreading coefficient	gridded, time varying winds and currents; variable resolution grid	Fay's 3 regime with turbulent dispersion	yes-Mackay in advection yes-Mackay	Mainframe	trajectory plot thickness, extent, shoreline impact, mass balance (variable resolution)
SLICK PC (AES)	emergency response, (AES)	winds, residual currents, tidal current, oil surface tension, spill location	uniform, time varying wind; uniform residual current; uniform time varying tidal current	Fay's 3 regime	no models	IBM PC or HP 9000	trajectory plot (1 nmile, 1 hourly time step)
SPILLSIM (Seaconsult)	emergency response, planning	winds, current model (residual, and tidal) , oil properties, waves	gridded, time varying wind and currents; currents from model,current atlas, or HF radar	Mackay	yes-Mackay yes-Buist yes-Mackay	IBM 486	trajectory, extent, thickness, mass balance (15 km square)

The model developed for the Beaufort Sea Coop by ASA (Applied Science Associates, Inc.) and subsequently modified by Gulf Canada Resources Ltd. is now specific to the Beaufort Sea due to the incorporation of a 3-dimensional hydrodynamic current module developed for the area. A unique characteristic of the model is its ability to specify ice edges via a painting technique. The ice edges are used in conjunction with ice concentrations to predict oil fate in ice (Jayko et al., 1991). Above 80% ice concentrations, the oil is assumed to be trapped or stored under the ice. Although the reliability and limitations of the model have not been fully assessed, the model is viewed as a useful tool for spill situations Table 2.1 and hindcast of spill scenarios (B. Wright, pers. comm.). Further development and testing of the model has stopped due to the low level of exploration activity in the Beaufort area.

The MIRG SL Ross model is an oil spill model that utilizes a 3rd party GIS (Intera-Tydac SPANS system) to handle its spatial data requirements (Note: MIRG - Marine Industry Group). Advection, spreading, evaporation, natural dispersion, and emulsification are accounted for in the model. This model is used by a consortium of oil companies in the Gulf of Mexico, mainly as a decision-making tool for dispersant use during contingency planning and emergency situations. Due to its unique built-in database of information, contingency planning and assessment of risk in a particular area are simplified (Trudel et al., 1989). The model can be implemented in any region by using the GIS system to create a map of the new coastline and resource database (Belore et al., 1990). The model has been verified with spill events such as the Ekofisk and the IXTOC 1 (I. Buist, pers. comm.).

OILBRICE, a model describing oil motion in broken ice, was developed by Fleet Technology and Crescent Consulting for the Atmospheric Environment Service (AES) of Environment Canada and the U.S. Minerals Management Service. S. Venkatesh of AES also contributed to the model development. It is presently being incorporated into a model under development by Greenhorne & O'Mara, Inc. for the US Minerals Management Service for use in US arctic waters. OILBRICE is said to be very flexible. It is designed to be used in conjunction with wind, ice motion, and ocean circulation models. The model uses empirical methods to determine the spread of oil in ice concentrations of 30-80%. The areal spread of

oil in ice provided by the model showed good agreement with the limited data measured by Ross and Dickins in 1987 (Venkatesh et al., 1990a,b). Greenhorne & O'Mara, Inc. hope to refine the model by December 1991 to identify oil mass under, over, encapsulated in, and coating the ice (S. Signorini, pers. comm.).

The Oil Spill Model Shell developed by ASA (Applied Science Associates, Inc.) is designed for use at any location world-wide. The input and output procedures have been standardized and an embedded geographic information system is used to manipulate environmental information. The model is designed to be used in either a forecast, stochastic, or receptor mode. To set-up the model within a minimum time frame in an emergency situation, data sets of probabilistic information on a world-scale are accessed (e.g., wind information from the International Station Meteorological Climate Summary, current information from the U.S. Navy Marine Atlas series). Verification of the model has been carried out for the Mina Al Ahmadi spill and the Cyprus Haven tanker spill, with results consistent with observations (Spaulding et al., 1991).

ASA is presently developing a state-of-the-art oil spill model called the World Oil Spill Model, for a consortium of industry and government clients including Environment Canada and the Canadian Petroleum Association. This new system is based on their Oil Spill Model Shell with various improvements such as the ability to incorporate a number of fate algorithms and operate on personal and laptop computers. The system is still under development and is expected to be finished in late 1992. ASA may also direct research projects to develop new fate algorithms for the model. Refer to Section 5.1.2 for a further discussion of the role of the Technical Advisory Group in directing the development of this model.

The ENSR OSP model is specific to the Chukchi and Alaskan Beaufort Seas. A unique feature of this model is a latitude and longitude grid system, which allows spill information to be tied to exact locations and entry of a variety of databases with different spatial densities. The OSP model takes into account the spreading of oil in ice and oil storage under

ice. Digitized contours of ice edge probabilities are used as input to the model (see Britch et al., 1990). It can be modified to apply to different areas as the environmental and shoreline elements are referenced by latitude and longitude. In order to do this, the model area would have to be redefined, shorelines digitized, and a residual current database entered. While the model has only been verified with one spill, the results appeared to provide reasonable agreement with observations.

The NOAA model, OSSM, can be operated in a tactical, statistical or receptor mode and can be used in any area. Wind and current (residual and tidal) data is input on a user-defined grids. Alternatively, the program can access a circulation model requiring bathymetry, shorelines, and a rough estimate of the residual current to generate current vectors (Torgrimson, 1981). OSSM has a flexible operating environment that can run on either the IBM PC or Macintosh II series of computers. Verification of the model has been completed with spills such as the Exxon Valdez (Galt et al., 1991) and the IXTOC 1.

Esso Resources Canada Ltd. is presently using the SCOOP model as a response tool for the Vancouver to Seattle tanker route (A. Holoboff, pers. comm.). The predecessor of SCOOP is SLIKTRAK, a model developed by Shell in the late 70's (Blaikley et al., 1977). The original program has been heavily modified and customized by Esso and renamed SCOOP. Because the model uses environmental input data from current atlases and real-time wind data, it is fairly transportable. The model was used extensively on the Exxon Valdez spill, and agreement with observations was dependent on the accuracy of the current and wind data (A. Holoboff, pers. comm.). SCOOP operates on a larger microcomputer (SUN workstation).

The AES (Atmospheric Environment Service) model, SLICK PC, is primarily used for emergency response by Environment Canada on the West and East Coasts of Canada as a first run simulation usually with a limited source of environmental information. It has no fate models incorporated into its framework and does not predict the impact of oil on shorelines (S. Venkatesh, pers. comm.). SLICK PC is intended to be a relatively simplistic

model to provide first estimates of spill trajectories during the initial stages of an event. The model has recently been transferred to the DOS operating system of the IBM PC.

AES also has a more complex model, SLICK II, developed and operated by S. Venkatesh at AES headquarters in Downsview, Ontario; this model is not available through the regional offices. Depending on the availability of environmental input data (preferably real-time data) a simulation can be performed in any marine environment. The model has the capability to input data in a variety of grid sizes and resolutions. It has been verified against data from the crude oil spills of the Exxon Valdez (Venkatesh, 1990c) using the limited public data available, the Argo Merchant, (Venkatesh, 1988) and the Beaufort Sea Minuk spill (S. Venkatesh, pers. comm.).

SPILLSIM, initially developed by Seaconsult ten years ago, has been revamped with updated weathering modules and improved hydrodynamic data. Recent applications include a detailed risk assessment of spills in Vancouver Harbour (Hodgins et al., 1991). Wind and current inputs include real-time gridded values or values generated from models for a particular area. Unique to this system is the ability to input real-time currents from HF radar. The hydrodynamic models have been calibrated and verified, implying a high level of confidence in the output of the model; however, no verification with an actual spill has been conducted (D. Hodgins, pers. comm.).

2.3 Oil Spill Trajectory Modelling Research

2.3.1 Primary Research

The research required to improve oil spill trajectory models can be broken into the following topics: advection, spreading, fate (changes in oil characteristics caused by evaporation, dispersion, emulsification and other chemical processes), and oil-in-ice interaction. The

emphasis of present efforts is on the environmental inputs (model, historical, or real-time values) and the fate of oil on the water.

Research in progress or conducted in the past year is summarized in Table 2.2 and described below. The statements describing the research were collected through personal communication with the researchers unless otherwise noted. The summaries focus on Canadian efforts. American research in the areas of oil spill trajectory modelling has been limited in the past several years, with some American research funds being spent in Canada. A review of recent proceedings (past three years) from oil spill-oriented conferences did not find any research papers dealing with trajectory modelling from SINTEF or other European research organizations.

Table 2.2 Oil Spill Trajectory Models: Research Efforts

Organization	Research Areas
Atmospheric Environment Service S. Venkatesh	shoreline impact aspects of model, improving user interface, oil in ice
Environment Canada M. Fingas	long-term evaporation, photo-oxidation, emulsification, and solubilization
Esso Resources Canada Limited A. Holoboff	improving evaporation algorithm, developing beaching algorithm, improving graphical display and user interface
SL Ross Environmental Research Limited	improving fate and behaviour algorithms, developing different spill scenario models
Seaconsult Marine Research Ltd. D. Hodgins	improving hydrodynamic models, interfacing to real-time measurement of currents with HF radar, interfacing with remote sensing data
University of Toronto, D. Mackay	improving algorithms for weathering and dispersion
Warren Springs Laboratory T. Lunel	droplet modelling of oil slicks

Atmospheric Environment Service (AES), S. Venkatesh,

S. Venkatesh is responsible for trajectory and fate modelling research efforts at AES. The new focus of his work is the improvement of the shoreline impact aspects of SLICK II. Physical processes such as the refloatation and retention of oil on the shoreline are two aspects that will be studied.

Research is being continued into the development of theoretical formulations for the behaviour of oil spills in cold and ice-infested waters. This is a continuation of an earlier study where some new concepts and empirical relationships were developed for spill behaviour in ice-infested waters (see Venkatesh et al., 1990a,b).

Environment Canada, M. Fingas

The Environmental Sciences Division, Environment Canada has started researching a number of fate processes: long-term evaporation (on the order of one month), photo-oxidation, emulsification, and solubilization. The objective of the research is to evaluate existing fate models and/or develop new ones. Extensive testing of each process and development of fate data sets will take place in order to verify the proposed fate equations. The projects are supported by PERD, Environment Canada, US Minerals Management Service, and the American Petroleum Institute. Each topic is estimated to require 2 person-years of effort. The results will be widely published; model developers will have access to the process equations and data through the literature.

Esso Resources Canada Limited, A. Holoboff

Present research is directed towards improvements of algorithms estimating the extent of oiling on shorelines, and modifications to the evaporation algorithm developed by D. Mackay. These efforts are close to completion. Because

improvements have been made rapidly, the documentation describing the changes is not yet finished. Any documentation will be initially proprietary to Esso Resources.

SL Ross Environmental Research Limited

Research efforts by SL Ross are concentrated on continued improvements to their fate and behaviour models. Additional work on their trajectory model includes the development of different spill scenarios such as blowouts from drill rigs or subsea pipelines. They are also continuing to improve the flexibility of the model to run on different operating systems.

They have developed two scenario specific models, WAXFATE and LEADFATE. WAXFATE uses simplified environmental inputs to determine the fate of waxy oils (see S.L. Ross Environmental Research and Mackay, 1988). LEADFATE takes into account oil behaviour in ice leads and the spreading and under -ice storage of oil (see Buist et al., 1987).

Seaconsult Marine Research Ltd.

Seaconsult is presently upgrading their 3-dimensional hydrodynamic high-resolution model for use with SPILLSIM (their oil spill trajectory model). This research effort has been in progress for the past three years with funding provided by DFO. Completion of the model known as GF9 is anticipated by the end of 1991. The model is useful for areas with a large estuarine influx such as the Fraser River in the Strait of Georgia.

University of Toronto, D. Mackay

Most oil spill models in North America incorporate some form of the fate and behaviour sub-models developed by D. Mackay. He is continuing work to improve and develop new algorithms for fate and behaviour processes for heavy crude oils. Present research includes testing and improving the

algorithms for evaporation, dissolution, and emulsification. The density increase of some oils is also being researched to evaluate the sinking of oil observed during spills. These processes will be verified with laboratory testing and comparison with available field data.

D. Mackay's funding is primarily from Environment Canada with some assistance from the U.S. Minerals Management Service and the University of Toronto. He regularly publishes his results in the proceedings of the annual Arctic Marine Oil Spill Technical Seminar (AMOP) and biennial Oil Spill Conference.

Warren Springs Laboratory, Stevenage, UK, T. Lunel

Work at the Warren Springs Laboratory includes research into the modelling of oil slicks as oil droplets to better predict observed effects such as the thick leading edge of a slick and the trailing sheens. The prediction of droplet behaviour determines spreading and dispersion. Based on observations, the total oil volume is divided into droplet sizes using a linear function. The equilibrium between droplet buoyancy and energy of breaking waves is solved to predict when the oil will resurface and its location upon resurfacing. Testing of the theory has taken place during a recent accidental spill in Europe. At present no papers have been published regarding this work.

2.3.2 Related Research

A related area of research which will have a major impact on operational trajectory modelling is the use of HF radar systems to map surface currents. Seaconsult Marine Research Ltd. is marketing a CODAR system called SeaSonde which will be tested in the coming year and could well be operational within that time. They will be able to provide real-time maps of sea surface currents for input to trajectory models. A similar system has

been developed at C-CORE. Raafat Khan (pers. comm.) reports that a portable system is operational. The system has been tested several times in Newfoundland. Some development effort would be required to provide user-friendly software for the C-CORE system and to develop an interface which would allow an oil spill model to conveniently access the CODAR data.

Environment Canada's recent workshop on trajectory modelling (DF Dickins Assoc., 1991) pointed to the need for considerable research in related areas to improve the operational capabilities of the models. For example, additional field measurements of oil behaviour in broken ice is required to verify the recent research models in this area. Current models are required in the Gulf of St. Lawrence, and, in general, the accuracy and completeness of ocean current information available for input into trajectory models (either from observations or hydrodynamic models) needs to be greatly enhanced.

3.0 CURRENT MODELS

3.1 Operational Users

Operational users of current models range from active users of ocean current forecasts to resource management users requiring models to understand fish migration and recruitment. Table 3.1 summarizes the needs of various users.

The primary users of operational models are search and rescue teams and response teams making decisions based on oil spill trajectory model predictions. Both of these users are primarily interested in the behaviour of the upper metre of water. Less direct, non-emergency users of operational current models are cargo-carrying vessels, the fishing fleet, and recreational boaters. These users require information on locations and times of high currents so that they can avoid those areas or plan accordingly. Mariners are not normally interested in predictions for areas where the currents are low (less than 1.0 knot).

While general circulation currents tend to be stable in time, surface currents are highly variable. For oil spill models and search and rescue applications, the dynamic behaviour of the surface current regime must be modelled in order to provide accurate forecasts of the trajectory of the slick or disabled vessels (e.g., MEP 1989). The main difficulty from a data input perspective is providing the necessary environmental data needed to arrive at reliable trajectory predictions in all Canadian offshore regions.

Both search and rescue and oil spill response teams require user-friendly programs with graphical displays of currents. For both these applications, it must be recognized that the users are usually not familiar with detailed oceanography and often need to consult with specialists from the Department of Fisheries and Oceans. (In the case of oil spill trajectory models, the users are typically government regional environmental emergency coordinators or oil spill specialists.)

Ideally, the users will be able to access current data directly in a form which is understandable for their application without further interpretation. Users are more likely to accept a model if they can retain control of the data and modify it with observations (as in the CANSARP software - CANSARP stands for the Canadian Search and Rescue Planning program, developed by Seaconsult Marine Research Ltd. for the Canadian Coast Guard (Seaconsult, 1985; 1988)).

Table 3.1 Current Models: Operational Users

Users	Desired Model Functions	Special Requirements
DND Rescue Coordination Centres	trajectory models for search and rescue	resource management and tactics
Oil spill trajectory models	surface currents (top 1 m)	user-friendly, high quality meteorological input
Oil & gas industry	current on risers and dynamically positioned vessels, search and rescue	3-dimensional current fields
Fisheries management, DFO	tidal and residual currents	density, salinity, water temperature
Fishermen, marine transportation, boaters	tidal currents, hazards	primarily areas of high currents
Iceberg drift models	surface and geostrophic currents	degree of use depends on iceberg model type
Sea ice models	surface currents	applies to models which use currents and are not presently capable of predicting them, most present models require residual currents

3.2 Operational Current Models

3.2.1 Model Characteristics

This review focuses on continental shelf modelling (from the coastline to the continental shelf break) as this regime is critical to oil spill trajectory models, search and rescue, and oil and gas exploration.

Currents on the continental shelf are a function of external forces (meteorological, tidal, surface gravity waves), internal forces and steering (density stratification, coriolis effect), boundary layer effects (shoreline shape, bottom topography), and bottom friction.

Models are classified according to the dimensions and types of effects modelled. Two dimensional barotropic models assume that the lines of equal pressure and equal density are parallel and that the water mass moves in one layer. Three-dimensional baroclinic models can describe currents that move through the vertical layers and thus account for all of the effects listed above (although many models choose not to predict tides or wave-current interactions). Baroclinic models are required in areas where density stratification is significant. Barotropic models which include some depth effects are often called 2 1/2-dimension models (see the following discussion of the OCS model).

Tidal currents are usually predicted with the simpler 2-dimensional barotropic models and often do not include meteorological forcing (i.e., wind, pressure).

3.2.2 Models Reviewed

While good ocean current data is critically important to support oil spill trajectory models, as well as a sea ice, iceberg drift, and search and rescue models, very few operational ocean current models are available.

On the West Coast operational models have been developed to predict the currents forced by tides and winds for search and rescue applications. The model DRIFTCALC, developed for search and rescue in Juan de Fuca Strait, benefitted from over 20 years of research by P. Crean and others at IOS (Institute of Ocean Sciences) (B. Crawford, pers. comm.). Fraser River discharge currents were added to the the model through doctoral thesis research conducted at the University of British Columbia. Seaconsult Marine Research Ltd. then developed the model into a search and rescue package, adding a user interface, leeway calculations, and other elements. The model, as embodied in DRIFTCALC, is based on a regular grid, has a tidal model and a gridded seasonal residual current database to account for the Fraser River discharge.

The TideView model, developed by Channel Consulting in cooperation with IOS, is a 2-dimensional finite element model based on the work of M. Foreman and F. Henry at IOS (see Henry, 1988). 10,000 nodes were used to create the variable triangular finite element grid for the model with resolution in some areas as fine as 100-200 m (A. Dolling, pers. comm.). It deals with multi-constituent tidal forcing and predicts the tidal currents in the Juan de Fuca and Georgia Straits (covering basically the same area as DRIFTCALC). The model allows the user to zoom into an area, automatically increasing the resolution as he does so. TideView runs on a PC and is aimed at recreational boaters. The main limitation of the model is that it does not include wind forcing. The model has compared favorably to spot observations, but an in-depth verification has not been carried out (A. Dolling, pers. comm.). Literature describing the model has yet to be published.

It is interesting to note that C-CORE is also working with Foreman's model to develop a tidal model for the Grand Banks (M. El-Tahan, pers. comm.). This is an instance where the transfer of a model to a different location has become straight forward and does not necessarily require a research scientist to set-up the model.

The CANSARP system is another search and rescue application related to current modelling. The program is an expert computer system that contains much of Canada's oceanographic

database (up to 1987) required for drift predictions. Current, drifter, and geostrophic flow data have been synthesized to give representative seasonal flow fields over much of Canada's East and West coasts, the Great Lakes, and the Gulf of St. Lawrence. Tidal current information is available for the Straits of Juan de Fuca and Georgia and is planned for the Bay of Fundy and the St. Lawrence system. CANSARP is also linked to CMC in Montreal to access weather data, both observed and forecast. Interfaces with remotely sensed ocean current data (CODAR) are planned for Fall 1991. No publication of the treatment of currents in the CANSARP system has been released to date, although a technical manual with a section describing the current data sources will be available next year (D. Hodgins, pers. comm.).

The Operational Ocean Current Modelling System (OCS) developed by The MEP Company in association with BIO (Bedford Institute of Oceanography) was designed to meet the needs of operational applications in coastal shelf waters (Scholtz et al., 1987). Such operational uses include oil spill emergency response, storm surge estimation, as well as ice and iceberg trajectory computations. This intended use placed a number of constraints on the complexity of both the model and the data requirements for model initialization and execution. For example, it requires as input only the data which can be reasonably obtained in an emergency response situation: CMC (Canadian Meteorological Centre) derived wind, pressure and temperature fields (hourly and synoptic input fields have been tested). The other input requirements (tidal constituents, bathymetry, background currents, density profiles) are satisfied when the model is set up for a specified domain.

The OCS is a 2 1/2-dimensional model that consists of a 1-dimensional finite element model of the time-dependent buoyancy and current profiles coupled internally through the depth integrated current and bottom stress with a 2-dimensional barotropic model. It is not a full 3-dimensional model because it can not predict the baroclinic component of flow, but the 1-dimension current profile model does provide information on current variations with depth. The barotropic model was developed at BIO by Greenberg (1983). The OCS has been tested

on the Scotian Shelf and has proven to be capable of accurately predicting surface currents (MEP 1985; 1988a and b; 1989; 1990).

The modelling system temporally and spatially interpolates the CMC data to meet the model time step (20 minutes) and grid specifications (8' x 8' latitude/ longitude grid). Open boundary conditions are tidally forced with an imposed radiation condition, and background circulation currents are simulated by adjusting the sea surface elevation and imposing a geostrophic flow at the northeast boundary.

While a number of the model performance tests have demonstrated the potential of the OCS in both forecast and hindcast mode, the model has several limitations for operational applications:

- it is site specific and therefore requires a significant level of effort to set -up in new domains
- it is presently implemented on a Cyber mainframe computer and is not user-friendly
- the 6-hour time steps of CMC meteorological fields limits the accuracy of the interpolated input fields which are required on a 20 minute time step.

Testing of the OCS suggests that future research should focus on the calibration of background flow and multi-constituent tidal forcing, improving user friendliness, and developing the model for other geographic areas.

ASA Consulting Ltd. (of Dartmouth) has a suite of numerical models which have been developed for various applications. Altogether seven generic models are available with several of these representing enhanced versions. Models are developed generically and run on a variety of platforms from Cray2 to PC. For models configured on the PC, ASA has a post-processor and graphical display shell that can provide animated displays of currents and

either linear superposition of solutions or non-linear superposition of response functions. Four of the ASA models are presented in Table 3.2.

The first, BARO-2D, has been set-up for the Scotian Shelf, Grand Banks, Labrador Sea, Hudson Strait, and Ungava Bay (Petrie et al., 1987; de Margerie, 1984; de Margerie and Lank; 1986). Currents are calculated using finite differences and semi-implicit integration. The model development started in 1984 in cooperation with D. Greenberg at the Bedford Institute of Oceanography using DFO and in-house funding. 2.5D-MULT is a slightly more sophisticated model, with local profile calculation using the Galerkin (finite element numerical solution) method and multiple time step semi-implicit integration. The model has been developed with support from AES Ice Central for use in their sea-ice models . Model results have been compared qualitatively to mean surface circulation on the Grand Banks and Labrador Shelf (Yao, 1990) and they fit the general circulation patterns. A third model, LAYERS, uses finite differences horizontally and vertically to predict currents in 2-3 layers. The model has been applied to Sheet Harbour and Halifax Harbour in Nova Scotia (de Margerie, 1989; de Margerie and Yao, 1989; Hurlbut et al., 1990).

Finally TIM, a 3 dimensional model, uses the finite difference horizontally, up to 10 basis functions with Galerkin method vertically, and time split semi-implicit integration. The model also allows changing geometry (due to drying mudflats). Typically 1000-5000 cells are used (for example, the Cumberland Basin model has 1000 elements, resolution of 400 m, 6 basis functions and runs in one quarter of real time on a PC). The model is an enhanced version of the 3D-HYDRO model, which was developed by Applied Science Associates, Inc. (an associated company in Rhode Island). The model has been applied to the Cumberland Basin and compared to current profiles and water levels collected during oceanographic cruises. Although available data showed a scatter of 20-30% in current values, the model predictions agreed with the mean vertical velocity profiles (for more details see de Margerie and De Wolfe, 1987a and b; and de Margerie et al., in press).

A summary of the operationally-oriented current models identified in this study is presented in Table 3.2.

Table 3.2 Summary of Operational and Near Operational Current Models

Model	Primary Purpose	Input Data	Model Type	Limitations	Configuration	Output
BARO-2D ASA Consulting Ltd.	storm surges, iceberg impact risk, oil spill models	winds, tidal constituents boundary cond.	finite difference, up to 3000 elements	barotropic	Cray2, Cyber, PC	printouts and plots (DISPLA post processor)
CANSARP Seaconsult	search & rescue all Canadian waters	CMC dial-up files of wind observations, time & date	2-D, internal residual current database, includes tidal model for Juan de Fuca & Georgia Strait	shoreline scale is coarse	Sun Spark workstation	trajectory maps wind field maps
DRIFTCALC Seaconsult	search & resuce Juan de Fuca & Georgia Strait	winds from wind stations, time & date	2-D, internal residual current database, includes tidal model	spatial resolution too low for back eddies	PC based menu, mouse interface	trajectory maps, 4 corners of search area
LAYERS ASA Consulting Ltd.	thermal effluent, water quality	winds, tidal constituents, boundary cond.	finite differences horz. and vert. 2-3 layers, up to 3000 elements	barotropic	PC	printouts and plots, animated display
OCS BIO and The MEP Company	oil spill trajec. search & rescue	CMC wind & pressure, temp. tidal constituents, density	2 1/2-D with background current boundary condition & tidal forcing 8' 8' lat/long grid on Scotian Shelf	barotropic, not easily moved to new locations	mainframe with link to CMC	maps of current vectors, current profiles, variable resoultion
Tidal models Mike Foreman, Falconer Henry IOS	tidal currents	bathmetry shorelines tidal heights at boundaries	2-D, barotropic, 10 consitutents variable, triangular FE grid	tidal prediction only	mini-computer: Reliant FX-40	maps of current vectors, variable resoution
TideView IOS & Channel Consulting	tidal currents Juan de Fuca & Georgia Strait	time & date	2-D, barotropic, 8 consitutents used for reconstruction, based on a variable, triangular FE grid	tidal prediction only	PC based, menu & mouse driven	2 day tidal heights, tidal currents

Model	Primary Purpose	Input Data	Model Type	Limitations	Configuration	Output
TIM ASA Consulting Ltd.	sediment transport	winds, stratification, tidal constituents, boundary cond.	3-D, finite difference horz., Galerkin method vert., 10 basis functions, up to 5000 elements	unknown	Cyber, VAX, PC	printout and plots (HP or Calcomp)
2.5D-MULT ASA Consulting Ltd.	mean circulation for sea-ice models	winds, local vert. profiles, boundary cond.	finite difference horz., Galerkin method vert., 20 km resolution on Labrador Sea and Grand Banks	tides not presently implemented	HP 1000, PC	printout and display post-processor

3.3 Current Modelling Research

On the West Coast, research models to predict residual and tidal currents are under active development at the Institute for Ocean Sciences. Work has recently started in Quebec to develop models for the St. Lawrence River estuary and the Gulf of St. Lawrence. On the East Coast, present efforts center on the Grand Banks. The general objectives of the research are to satisfy the need to understand fish migration patterns, and provide current data to oil spill trajectory models.

Very little research has been done on circulation models in the Great Lakes since the work of Simons in the 1970's (Simons, 1975; 1976). The recent focus has been on modelling and measuring currents in local areas as part of ongoing research on water quality (P. Hamblin, pers. comm.).

The research efforts currently underway or planned in Canada are summarized in Table 3.3 and described in more detail below. Unless noted otherwise, the details presented have been collected through personal communication with the researchers. Current models by nature tend to be location specific; the techniques of modelling themselves may be derived from research carried out in other countries. Instances of this have been noted in the summaries below where known.

Table 3.3 Current Models: Research Efforts

Organization	Research Areas
C. Anderson, Bedford Institute of Oceanography	setting up OCS model on Grand Banks, implementing multi-constituent tidal forcing
B. Crawford, Patrick Cummings, Institute of Ocean Sciences	residual current models of B.C. waters
M. Foreman, Institute of Ocean Sciences	2 dimensional tidal models of B.C. waters
R. Greatbacht, Memorial University of Newfoundland	2 and 3-dimensional shelf models for the Grand Banks and North Atlantic
D. Greenberg and J. Loder, Bedford Institute of Oceanography	finite element modelling techniques running research models within a PC environment
V. Koutitonsky, Institut Nationale de la Recherche Scientifique	3-dimensional model of the St. Lawrence estuary

C. Anderson, Bedford Institute of Oceanography

C. Anderson has implemented changes designed by The MEP Company to include multi-constituent tidal forcing (M_2, S_2, N_2, K_1 and O_1) in the BIO/MEP Operational Ocean Current Modelling System (OCS). At the same time, efforts are under way to set-up the model on the Grand Banks of Newfoundland. This work is not yet complete and it has been learned that Dr. Anderson has recently taken a research position associated with Dalhousie University (D. Lawrence, pers. comm.).

B. Crawford, P. Cummings, Institute of Ocean Sciences

B. Crawford and his associates are developing residual current models for the Queen Charlotte Islands area of British Columbia (northern Hecate Strait and

Dixon Entrance). With funding through PERD, C. Hanna at the University of British Columbia has developed a 2-dimensional barotropic wind-driven model for this area and B. Crawford is verifying the model through a series of tracking and moored buoy deployments. The next major step in model research will be the development of a 3-dimensional, wind-driven baroclinic model for the area. Model development and verification is an ongoing process that is expected to continue for the next 10 years. A key objective is to provide current models for prediction of oil spill trajectories, although the models also have applications in fisheries management (Crawford et. al, 1990).

Initial results from the verification indicate that the 2-dimension model is not accurate in Dixon Strait and will require further development (B. Crawford, pers. comm.). The present model has been used in an operational sense to predict movement of fish eggs and larvae, but the computation time is too slow to produce more than 2-3 months of hindcast data. The most important limitation at the moment is the complexity of coastal B.C. oceanography. Another problem is the provision of wind fields around islands and other orographic features. Operational implementation can begin once the researchers feel that model accuracy is suitable.

M. Foreman, Institute of Ocean Sciences

M. Foreman has developed 2-dimensional barotropic tidal models for various B.C. waters. He completed a model for the southwestern coast of Vancouver Island (Foreman and Walters, 1990) and is now working on a model to cover the waters from northern Vancouver Island to the Alaska Panhandle. Also planned or underway is upgrading of the Juan de Fuca Strait model developed by IOS and filling in of the area between Vancouver Island and the mainland. As well, preliminary development of 3-dimensional models incorporating salinity and wind-forcing has started. The tidal model for the Queen

Charlottes will be combined with the residual current model for the area (see B. Crawford above). The impetus for the models comes through a need to understand salmon migration patterns.

The model developed for the southwest coast of Vancouver Island assumes uniform water density, no vertical component to the currents, and uniform horizontal currents with depth. Ten tidal constituents are used. Although the tidal heights and phases are favourably predicted, the tidal flow would be improved by including baroclinic effect (Foreman and Walters, 1990).

It takes six months to a year to develop the model for a section of coast. The models are based on a triangular finite element grid of varying size (depending on the detail wanted in particular areas). The grid is generated from a package of computer programs developed by F. Henry at IOS (Henry, 1988) which significantly reduces the time required to generate and refine grids. Boundary conditions are specified as tidal heights (Foreman and Walters, 1990). Collecting current measurements for the models consumes a significant amount of effort.

Development of the models for operational use will require parameterization of the predicted currents.

R. Greatbacht, Memorial University of Newfoundland

R. Greatbacht has been involved in the development of several barotropic models for North Atlantic regions. Two wind-driven barotropic models describing seasonal circulation have been developed for the Labrador Sea and North Atlantic and work has recently been completed on a shelf model for the Grand Banks (volume flow with no wind-forcing) (R. Greatbacht, pers. comm.). Results from the shelf model indicate that a full 3-dimensional model incorporating wind is required. For the shelf model, boundary conditions were

specified on the northern boundary and open along others, while land was modelled as shallow water. Associated scientists are collecting data for model verification. Tidal information has not been included in any of the models at present. Funding for the research is primarily through the OPEN Network of Centers for Excellence program, NSERC and WOCE (World Ocean Circulation Experiment).

D. Greenberg and J. Loder, Bedford Institute of Oceanography

D. Greenberg and J. Loder, are presently developing 3-dimensional finite element models in an effort to simulate ocean currents at high resolution for specified target areas. They are particularly interested in modelling baroclinic forcing given specified density fields. This work is being carried out in the Gulf of Maine and Georges Bank in association with D. Lynch (Dartmouth College) and F. Warner (Skidaway Institute of Oceanography). Lynch and Warner (1990) are considered the leading experts in the use of finite element grids and the development of finite element algorithms for the full equations of motion. Greenberg and Loder are also coordinating their research on finite element modelling with M. Foreman at IOS. They are running their models on a Data General Work Station and a Stardent Mini Super Computer.

This research effort appears to be several years away from being used in an operational setting; nevertheless, the studies will be instrumental in understanding the flow behaviour in the coastal ocean. The work demonstrates a research to research linkage and software exchange between U.S. and Canadian scientists concerned with modelling the motions in the ocean.

V. Koutitonsky, Institut National de la Recherche Scientifique, University of Quebec

A 3-dimensional, general circulation, finite difference model is being developed at the INRS (Institute Nationale de Recherche Scientific) for the St

Lawrence estuary. The model extends from Quebec City seaward to approximately Sept Iles. The grid is curvilinear-orthogonal in the horizontal direction and increases in spacing from 1 km to 2-3 km as the model domain moves into the Gulf of St. Lawrence. A sigma coordinate system is used vertically (thickness of levels increase with depth). The modelling techniques are derived from the work of two U.S. researchers: Mellor and Bloomburg. Presently the model includes tides, salinity, wind-forcing, and eddy propagation. The effects of ice cover will be included at some point in the future. The model requires seasonal type data (seasonal winds, fresh water outflow, tides) for initial conditions. The research model is being developed on a HP 9000 workshop and will be transferred to a DFO Stardent Mini Super Computer.

Various boundary conditions are being examined for use at the estuary boundary of the domain. The east boundary will be open and defined by measured conditions. Cruises are planned in the Gulf of St. Lawrence next year to collect data for the open boundary. Data was gathered in the estuary last year for calibration of the model.

The model development was started last year and will continue up to March 1993. Once the 3-dimensional model is complete, a transport model for prediction of subsurface chemical transport and a surface transport model for prediction of oil slick movement will be developed. Publication of the results will begin to take place next year (work at this point in time is too preliminary for publication).

4.0 WAVE MODELS

4.1 Operational Users

Users of wave models can be divided into two categories, AES and the oil and gas industry, each approaching model operation quite differently. AES may be classified as an operator rather than a user of wave models; the models are used to provide marine forecasts for mariners (fishermen, recreational boaters, and the commercial shipping industry). The oil and gas industry uses wave forecasts directly, and normally employs contractors to operate the models and provide forecasts. The private contractors typically use purchased models which may have some in-house customization added.

The main concern of the AES marine forecasters is retaining the ability to control the wind field data. To this end they require a user interface that will allow them to quickly modify wind and pressure fields. Although considerable effort has gone into the user-interface in the most recent models, forecasters are still not completely satisfied (O. Lange, pers. comm.). AES in Vancouver commented that the wave models are not efficient if the forecaster requires more than 0.5 hours at the user interface to produce a forecast (M. Horita, pers. comm.). The forecasters prefer graphical output (typically in the form of contour maps of wave height).

The needs of oil and gas drilling operators have been reviewed in Hodgins and Hodgins (1988) and are presented in Table 4.1. Hodgins and Hodgins found that drilling operators prefer forecasts for at 1 hour intervals up to 12 hours and then for at 6 hour intervals up to 48 hours, but were skeptical of more advanced forecast products such as platform motion response. Drilling operators use forecasts to plan activities such as crane operations, transfer of personnel, supply boat offloading, and anchor handling.

Table 4.1 Desired Wave Forecast Requirements for Offshore Oil and Gas Drilling Operations (after Hodgins and Hodgins, 1988)

Note: all parameters were desired for 12 hrs at 1 hr intervals and from 12-48 hrs at 6 hr intervals.

Parameter		Precision	Accuracy (all intervals)
wind sea	- sig. height	0.3 m	± 8%
	- sig. period	1 s	± 10%
swell	- sig height	0.3 m	± 8%
	- period	1 s	± 10%
	- direction	8 pts compass	± 20%
combined sea	- sig. height	0.3 m	± 8%
	- period	1 s	± 10%
	- max height	0.3 m	
spectrum	- 1D	15 freq. bands4	$\sqrt{m_o}$ within 15%

Note: $\sqrt{m_o}$ - root mean square

Drilling operators in the Beaufort Sea require models which can accurately predict waves in a regime dominated by shallow water effects; marginal ice-zone effects; fetch-limited wave growth; duration-limited wave growth; sheltering effects (wave diffraction) by islands and irregular shorelines; and wave-current interactions. At present, no operational wave models are being run in the Beaufort Sea; however, hindcast studies of storm events have been completed using the Ocean Data Gathering Program (ODGP; see Agnew et al., 1989), and subsequently, under a PERD/ESRF project, additional hindcasts of 34 "severe wave-producing storms" have been recently completed (V. Swail, pers. comm.). The end users of this information will be the design and operations engineers for the offshore operators and the government regulatory agencies.

Mariners do not require the same level of information as drilling operators (Hodgins and Hodgins, 1988). Combined wave height, swell, and swell direction (if different from the wind direction) meets the needs of most mariners.

4.2 Operational Wave Models

4.2.1 Model Characteristics

Operational and research wave models can be classified as parametric wave height, parametric spectral, or discrete spectral.

Parametric wave height models predict monochromatic expression of wave height and period based on fetch and wind duration. Parametric spectral models solve the conservation of energy equation as a function of time and use the result to compute the change in energy at the point of interest. Energy is represented as a frequency spectrum.

Discrete spectral models represent the wind field in terms of an energy spectrum that is in a local balance with the advected wave energy, energy growth due to the wind, and dissipation due to white capping. The discrete models describe the 2-dimensional spectrum in terms of a finite set of frequencies and directions.

Table 4.2 lists examples of these three types of models.

Table 4.2 Operational Wave Models

Parametric Wave Height Models

AES Parametric Model

Parametric Spectral Models

Hasselman's parametric spectral models

NORSWAM: a hybrid model for wind-sea and swell

GONO: the Dutch operational forecast model

*Donelan's Model

The Ross Hurricane Model

The Norwegian Model

Discrete Spectral Models

SOWM and GSOWM: the FNOC Models

*ODGP: Cardone's modelling efforts

*WAVAD: Resio's modelling efforts

System 21: the Danish Hydraulic Institute Model

BMO: the British Meteorological Office

*SPECREF: Seaconsult Marine Research Ltd.

WAM model: WAM

* Denotes models used in Canadian waters - the focus of the present study. A detailed review of the other models is available in Hodgins and Hodgins (1988) and The WAMDI Group (1988).

4.2.2 Models Reviewed

Operationally-oriented models adopted for operational applications in Canadian waters have their origins in one of four models: (1) ODGP (which is the source model for CSOWM and

PACWAV); (2) WAVAD, which is the source model for DWAVE; (3) Donelan's model; and (4) SPECREF.

The Ocean Data Gathering Program (ODGP) is a modelling system with first, second and third generation growth terms which has been developed by Dr. V. Cardone of Oceanweather, Inc. The main features of the ODGP are discussed in Cardone et al. (1976). It has been constructed in two basic parts: the first part affects propagation of waves through a grid; and the second part simulates, at each time step and grid point, the change to each spectral component of the directional spectrum, caused by growth and dissipation. The growth/dissipation algorithms are routinely applied to a spectrum partitioned in 15 frequency bands and 24 directional bands.

As noted above, the ODGP is the source model for AES's Canadian Spectral Ocean Wave Model (CSOWM). CSOWM has been producing operational forecasts for the East and West Coast of Canada since November, 1990 and January 1991, respectively.

For the northwest Atlantic region, the model physics includes shallow-water processes of wave refraction, wave shoaling and bottom friction; these processes are excluded from the northeast Pacific region because the nearshore regions are deep (Khandekar and Lalbeharry, 1990). The CSOWM also includes as an optional package, the explicit calculation of the 3G source terms to simulate the nonlinear wave-wave interaction processes.

For the northwest Atlantic, the CSOWM is run on the CRAY XMP at the Canadian Meteorological Centre (CMC). The model inputs are derived from the CMC finite element model 10 m wind fields which are available on a 100 km grid. The CSOWM operates on a latitude/longitude grid with both coarse and fine resolutions (1.084 and 0.36133 degrees of longitude respectively).

The CSOWM has been set up to operate in the northwestern Atlantic in six different configurations: 1G (first generation) coarse grid; 1G coarse plus fine grid; 1G coarse plus

fine grid plus shallow water physics; 3G coarse grid; 3G coarse plus fine grid; and 3G coarse plus fine grid plus shallow water. The run times for these different options are presented on Table 4.3. AES is currently testing the model under these different modes but at present only the 1G coarse grid version of CSOWM is operational.

For the northeast Pacific the CSOWM is also run on the CRAY XMP but in this case the model inputs are derived from the CMC spectral model 1000 mb wind fields which are available on a 381 km grid. The reason for using this input is largely logistical, the spectral model wind fields are available for the local times needed on the West Coast while the finite element model grid does not cover the grid used by the wave model. The CSOWM is operated on a coarse and fine grid on the West Coast (1.2228 and 0.4076 degrees of longitude respectively).

Table 4.3 CSOWM Northwestern Atlantic Estimated Run Times
(in minutes for 16 three hour time steps, assuming 30 seconds for compiling)

Model Complexity		Computer		
		CRAY XMP	HP9000 ^00	HP9000 720
Coarse	first generation	0.84	38.82	6.5
Coarse+Fine$_{deep}$	first generation	2.44		
Coarse+Fine$_{shallow}$	first generation	9.88		
Coarse	third generation	14.09		
Coarse+Fine$_{deep}$	third generation	26.25		
Coarse+Fine$_{shallow}$	third generation	34.15		

Note:		
	Coarse	60 nautical mile resolution, deep water physics
	Fine$_{deep}$	20 nautical mile resolution, deep water physics
	Fine$_{shallow}$	20 nautical mile resolution, shallow water physics

The CSOWM is run every 12 hours and produces as output a significant wave height chart for 0, 12, 24 and 36 hours from time zero. This is essentially the same output as generated

by the AES Parametric Wave Model which is no longer in operation. The CSOWM charts is provide a better distinction between sea and swell. It should be noted that the southern boundary used in the CSOWM grid will result in missing some swell in the forecasts.

PACWAV, the Pacific Wave Model used at the Pacific Weather Centre was also derived from the ODGP with the first generation (1G) physics for the source and sink terms. PACWAV has been set up on an HP9000 workstation within a user-friendly shell for operational use by the Pacific Weather Centre. The coarse grid version of PACWAV is 1.25 by 2.5 degrees and the fine grid is about half of the coarse grid.

PACWAV's user-friendly shell allows the user to capture the CMC spectral model wind and pressure fields and to change these input fields operationally in a dynamic fashion before running the model (V. Swail, pers. comm.). The modifications possible include: changing intensity and moving pressure centers, changing air and sea temperatures (and therefore stability), and locally adjusting wind speed and direction. From an operational forecast point of view, these adjustments can significantly improve the model predictions and the changes can be done very quickly. Similar adjustments are not done to the inputs used in CSOWM. From a research point of view, this user-friendly software prepared by AES (Meteorological Services and Research Branch specifically) provides the model developers with an excellent system for kinematic analysis. V. Cardone has expressed an interest in the software package to this end. This represents an interesting linkage from the operational scene back to the model developers.

An HP 9000 version of the ODGP has also been set up in METOC office for operational use along the Atlantic Coast. Feedback from the end users is only starting at this time and full evaluations have yet to be made. Nevertheless, a one month evaluation from the METOC office suggests that the forecaster estimates from wave nomograms were better than the ODGP output at 12 and 24 hours from time zero, while at 36 hours the two estimates are comparable (A. Bealby, pers. comm.).

The main problem the forecasters appear to have with the wave model is associated with model credibility. This will improve with continued calibration and continued model performance testing of the model. At this point, it appears that the ODGP (CSOWM, PACWAV) are still competing with the simple wave nomograms used by experienced forecasters.

The WAVAD Model was developed by D. Resio (now at the Florida Institute of Technology); it may best be described as a coupled discrete spectral model. The theoretical aspeets of WAVAD have been presented in a series of papers by Resio (1981, 1982, 1987, 1988) and earlier by Resio and Vincent (1977). WAVAD assumes that the dominant source/sink terms are wind, wave breaking and frictional dissipation, and under active wave generation (i.e., still under wind forcing). The nonlinear flux plays a central role in preserving self-similar spectral shapes. The modelling procedure ignores wave/current interaction (as do most deep water operational models) and wave diffraction and reflection.

WAVAD is being used by Oceanroutes (Canada) Inc. on the East Coast and by Seaconsult Marine Research Ltd. on the West Coast. The model is also being tested in the Great Lakes by the U.S. Army Corps of Engineers under the name DWAVE. The exact specifications for the operational use of this model are not presently available.

SPECREF is a decoupled propagation model, developed by Seaconsult Marine Research Ltd., to give the directional wave frequency spectrum at a specified location. SPECREF is similar to WAVAD in terms of the procedures for evaluating refraction and shoaling. Both use a saturation spectrum (the energy spectrum for a fully developed sea) to limit energies at frequencies above the peak frequency, but the form of the saturation spectrum differ. The models are fundamentally different in the specification of the wind source term and the partitioning of energy between different parts of the spectrum. For this reason, the models were compared with observational records from the Sable Island Bank (Hodgins et al., 1989). Both models were concluded to be suitable for shallow water hindcasting.

SPECREF is used in hindcast mode on the Great Lakes to provide the necessary wave data for the engineering design of coastal structures. Seaconsult views the model as operational as part of their Seaweather software system which is available for B.C. coastal waters (Hodgins and Berglund, 1989).

The Donelan model is a parametric spectral model developed by M. Donelan (Canada Centre for Inland Waters). The technical attributes of the model are discussed in a paper by Schwab et al. (1984). Working with directional spectra measured off Van Wagner's Beach (Western Lake Ontario), Donelan et al. (1982) modified the JONSWAP spectrum (Hasselmann et al., 1973) to produce a spectral form which yields a smooth transition between very narrow spectra (characteristic of young waves) and the broader, fuller developed spectrum (defined originally by Pierson and Moskowitz, 1964). This makes the model particularly suitable to fetch-limited water bodies, like the Great Lakes and the Beaufort Sea.

The Donelan model is run operationally at the Ontario Weather Centre every 6 hours using the marine wind forecasts (FCN20's). The input data is sent to CMC and the model is run on the CRAY XMP for selected sites in the Great Lakes (particularly Lake Ontario). Forecasts for the next 24 hours are produced and the information is released to the Canadian Coast Guard who are responsible for releasing it to the end users (primarily recreational boaters).

Donelan's model has been tested for operational use in the Beaufort Sea (Clodman and Eid, 1988), but at present, no operational models are running in this environment.

The attributes and limitations of the five operational models discussed are summarized in Table 4.4. The other operational models listed on Table 4.2 are not presently used in Canada and are therefore beyond the scope of this study. Most of these models have been recently examined in detail by Hodgins and Hodgins (1988) and The SWAMP Group (1985). Section 5.4 identifies the linkages between the Canadian wave modelling community and international research and development.

Table 4.4 Summary of Canadian Operationally-Oriented Wave Models

Model	Primary Purpose	Input Data	Model Type	Limitations	Configuration	Output
CSOWM	CMC and METOC forecast for East Coast	*CMC gridded wind fields	1 G spectral model	shallow water effects, CMC winds used as is, out of grid swell	CMC CRAY XMP	4 panel map of sig. wave height, & period, swell, direction
Donelan's model	forecasts for Ontario Weather Centre	marine wind forecasts	parametric spectral model	sallow water effects	CMC CRAY XMP	sea state at specifc locations
PACWAV (MacLaren Plan-search, Resio	Pacific Weather Centre forecasts	CMC isobaric field, local observations	1G spectral model	shallow water effects, out of grid swell	HP 9000 work-station mouse	sea state, spectral energy, swell
SPECREF Seaconsult	forecasts B.C. coast	CMC/surface wind forecasts	decoupled propagation model	site specific	PC with 2400 baud line communication	refraction diagrams
WAVAD (Don Resio)	hindcasts forecasts by Oceanroutes	gridded wind field data	2G coupled discrete model	no wave-current interaction or wave diffraction and reflection	IBM 386	sea state at site

Notes: 1G, 2G - first generation, second generation
* different inputs are used for the east coast (CMC finite element model 10 m winds) and the west coast (CMC spectral model 1000 millibar winds

4.3 Wave Modelling Research

On a national level the National Waves Committee focusses on wave research (through W. Perrie, M. Donelan, and D. Masson), wave hindcasting and forecasting (CSOWM) as well as the establishment of a regional model in the Pacific Weather Centre (PACWAV) (V. Swail, pers. comm.). This ad hoc committee coordinates the efforts of researchers among themselves and with the needs of industry and government users.

The international research effort in wave modelling is reasonably well organized through the WAve Modelling Group (WAM); almost all of the key model developers are members of this international group which meets periodically to discuss research needs and directions. The link between the researchers and the operational personnel is established in part by this group. For example, AES scientists are invited to the WAM meetings.

Another wave modelling group which is having an international effect is NESS (North European Storm Study). This large wave research effort in the North Sea involves 10-12 petroleum companies as well as a number of wave researchers around the world. According to V. Swail (pers. comm.) the study has included wave hindcasts for 25 six month winter periods and the analysis of an additional 25-30 severe storms. The third generation WAM model is being used for the modelling component of the study. To date the data collected have not been published and remains proprietary.

The research efforts currently underway or planned in Canada are described below.

S. Clodman, Atmospheric Environment Service

S. Clodman continues to refine the parametric wind wave models (which are based on the SMB empirical approach or Donelan's work (1977)) (see Clodman 1989a and b). He has recognized their computational efficiency and utility for operational forecasting in fetch restricted water bodies where swell

can be ignored (e.g., the Great Lakes, Beaufort Sea) He questions the wisdom of using advanced models where we are not capable of supplying the necessary inputs or testing the model outputs.

M. Donelan, National Water Research Institute, Canada Centre for Inland Waters

M. Donelan has recently been involved in the Surface Wave Dynamics Experiment (SWADE) which was conducted off the coast of Virginia from October 1990 to March 1991. SWADE represents a multi-national effort which was initiated and largely financed by the U.S. Office of Naval Research. SWADE's scientific goals include: (1) understanding the dynamics of the evolution of the wave field in the open ocean; (2) determining the effect of waves on the air-sea transfer of momentum, heat, and mass; (3) exploring the response of the upper mixed layer to atmospheric forcing; (4) investigating the effects of waves on the response of various airborne microwave systems including radar altimeters, scatterometers, and synthetic aperture radar; and (5) improving numerical wave modelling. Addition details on the experimental design and instrumentation are presented in Weller et al. (1991). Despite the loss of the Spar buoy during the early phase of the field experiment, SWADE was a success (M. Donelan, pers. comm.) and the data are presently being examined.

M. Khandekar, Atmospheric Environment Service

M. Khandekar is presently examining the various options for running the CSOWM operationally. The focus is on model performance versus model run time on the CRAY XMP. He is AES's representative in the WAM group and his work provides a key link between the model researchers and the operational end users.

D. Masson, Institute of Ocean Sciences

D. Masson is studying wave-current interaction with PERD funding. She is trying to determine the conditions under which current interactions are significant in wave processes. The predictions of a Dutch wave model, HYSWA, which contains current interaction equations, will be compared to field measurements collected this summer by HF radar techniques in Hecate Strait, B.C. The verification results will indicate the conditions under which the theory present in the model is valid, while the research will also provide indications of when wave-current interactions are significant. As yet there is no published literature on this work. She estimates that this research will be finished in two years. The final product will recommend ways to implement the theory in numerical models. Considerable development will be required to implement the results in an operational model.

W. Perrie, Bedford Institute of Oceanography

W. Perrie is involved in several projects ranging from pure research to studies of operational models. Through PERD funding he is studying data assimilation (particularly satellite data) into wave models as well as wind-wave coupling. He plans to use the ERS-1 satellite to provide surface wind fields and wave height data for research into the coupling at the boundary layer. The effort in data assimilation is outlined in a report by Hasselmann et al. (1990). Essentially the research focuses on ways to represent the sea surface as "seen" by the satellite in the wave models. This will provide the models with a better approximation of energy already present in the wave field. Perrie feels that it will take several years to understand boundary layer coupling and to incorporate the results into operational wave models. Although ERS-1 is not an operational satellite it may be possible near the end of its lifetime to incorporate ESR-1 data into operational models (L. Gray, pers. comm.).

Other Bedford Institute of Oceanography researchers working in related areas are complementing these studies. F. Dobson is studying sea surface drag and

is planning a field program to groundtruth the ESR-1 satellite data in November. S. Smith is studying air-sea flux momentum.

5.0 OPERATIONAL/RESEARCH LINKAGES

Linkages were studied in terms of: (1) the relationships between four key groups involved in wave, current, and oil spill modelling: researchers, developers, operators and users (refer to Figures 5.1 and 5.2 for a conceptual representation of the linkage paths); and (2) the relationship between operational and research models themselves.

A primary objective was to identify areas where the operational utility of models could be enhanced by better communications, or by improved information transfer between the various groups involved the evolution or creation of new models.

The following subsections explore the linkages between human resources within the sphere of each generic model type, and the linkages between the models themselves. The opinions expressed here are based on discussions with people active in the field.

Several agencies were contacted in an effort to identify references which would relate to these discussions or support the personal opinions expressed in this report: Industry Science and Technology Canada, The Science Council of British Columbia (as an example of a technology transfer at a provincial level), Canada Institute for Scientific and Technical Information (CISTI), and the National Research Council of Canada. The references and theme papers invariably dealt with the problem of technology transfer leading from research to a commercial product. Problems faced during product development for the marketplace are very different from those affecting the effective transfer of research mathematics or processes into operational models.

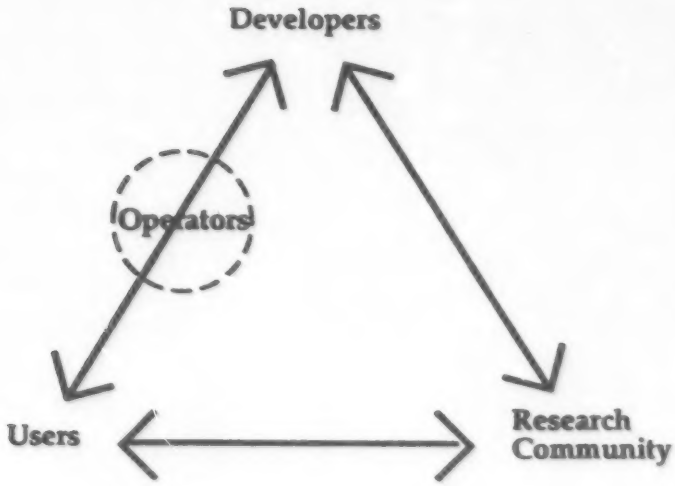

Figure 5.1 Linkages: Oil Spill Trajectory and Current Models

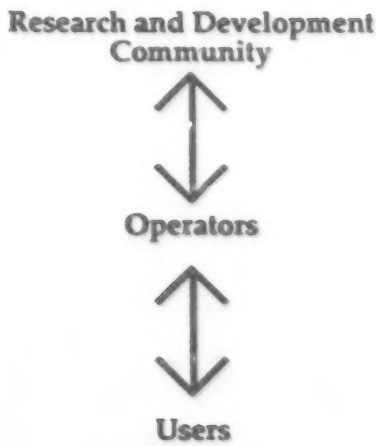

Figure 5.2 Linkages: Wave Models

5.1 Oil Spill Trajectory Model Linkages

Researchers ↔ Developers

Linkages between research and operations are strongly dependent on the scientific background of the individual developers. The majority of model developers can be classified in one of two groups: oil spill specialists with a background in chemistry, or current modellers with a background in oceanography. Each group tends to focus naturally on their own expertise, and to use their familiarity with particular scientific literature to strengthen the model in certain areas. For instance, oceanographers (Applied Science Associates, Inc., Seaconsult Marine Research Ltd.) take advantage of their in-house expertise in current modelling to develop the advecting current component of the trajectory model.

Operational models incorporate algorithms describing a number of different physical or chemical processes; these processes (e.g., advection, spreading, evaporation, dispersion, emulsification) are most often investigated by independent researchers having no direct affiliation with the overall model development. Research results are published widely, and it is left to the model developer to incorporate the most applicable results into a particular model; this process could lead to personal bias in deciding which algorithm to include, or, depending on the degree of familiarity of the developer with recent literature, could lead to the selection of an inappropriate or incorrect algorithm for a specific application. The linkage in this case is remote and appears to work best when the researcher and developer have backgrounds in similar disciplines.

One problem is that many pure researchers may lack an appreciation of how to express physical processes in a manner which is readily assimilated by engineer developers.

The general opinion of a number of developers surveyed in this study was that there would be little if any benefit from trying to involve researchers directly in model development. Their argument was that researchers operate in a very different work environment than

developers and would rather not deal directly with practical applications, an attitude which could be viewed as representing a somewhat outdated and stereotypical view of the research world.

It is recommended that PERD continues to explore ways in which researchers (and users) can be more actively linked to the model development process as it proceeds. The ongoing participation of the Technical Advisory Group in directing the progress of the state-of-the-art oil spill model system (ASA - 1991/92) is a good example of how scientists/users/developers can interact throughout the development process.

The principal weakness in the existing linkages between the researchers and developers is that they are often remote, with the two groups communicating through the mechanism of published literature. This lack of direct communication is to the detriment of the developed model; not only is the developer often left with a difficult choice of the "correct" or most appropriate algorithm, but the most recent (improved?) research results may not find their way into the operational model. Also, the developer may not fully understand the limitations on applying the research results in an operational setting (e.g., valid boundary conditions or constraints on certain parameters).

Developer ↔ User

A second important linkage pathway occurs between the developer and the user; interposed between these two groups is the operator. In some cases, the developer and the operator are the same (e.g., Venkatesh's SLICK II research model which can be run operationally on request), and in other cases the user and the operator are the same (i.e., Beaufort Sea Coop). There are cases where the model operators and users form two distinct groups, as in the federal government where the Atmospheric Environment Service regional offices (the operators) run a simplified oil spill model, and deliver the results to Environment Canada's Regional Environmental Emergencies Coordinator (the user).

Within Environment Canada, linkages between model operators in the regional offices and model developers are well established. The regional offices comment regularly on the performance of a model through the research manager at AES headquarters (B. Beale, pers. comm.). For example, to develop Slick PC, AES headquarters tested a prototype in one of the regions and collected extensive feedback to incorporate into the final operational version (S. Venkatesh, pers. comm.).

There is no formal mechanism within the government for the user to comment on the model output and pass comments back to the developers (R. Simmons, pers. comm.); vocal criticisms are often heard about a particular model's poor performance in an emergency situation, but in the case of government models, it is not safe to assume that constructive comments are passed back to the developers. One way of overcoming this deficiency would be to invite the model developer to a formal debriefing following an incident or to invite the developer to participate directly in verification exercises.

Industry and government often rely on private developers for models; this may involve the development of an entirely new dedicated model or the modification of an available product to suit a particular offshore area (e.g., recent Beaufort Sea Coop procurement of the ASA model - 1990). Situations can exist where a model is developed and delivered without any substantial involvement of the user in the details of the processes or programming language. The inevitable need for updates and refinements to the "prototype" or first release version can lead to frustration as the user struggles with a lack of in-depth knowledge, or adequate documentation; the end result of this process can be extremely wasteful, and in the worst case leads to scrapping of the original model and a repeat of the contracting process. A pro-active approach by the participants (or contracting authority) in both the management and the science of commercial model development is the best way of insuring against such an outcome (refer to Section 5.1.1 for a discussion of an ongoing example of this approach).

Alternatively, a developer may market an off-the-shelf model (the model may require some location-specific development to suit particular users). Developers rely on feedback from

previous clients and usually endeavour to provide the best of what is available operationally (D. Hodgins, pers. comm.). In this case there is a strong commercial incentive to understand the problems with existing models, as well as the detailed requirements of a number of potential clients.

It is noted that, the linkages between developers and users linked through a contractual relationship are more likely to be strong and effective (compared with internal government programs). This is not surprising given that serious financial or operational penalties are incurred on both sides if good communications are not maintained (the user ends up with a deficient model, and the developer ends up with an unsaleable product or expensive cost overruns). In the user's case, a seriously defective model could jeopardize applications for drilling permits worth hundred's of millions, while the developer who has not responded to the clients needs could be placed in financial jeopardy through a loss of income.

There are ways to ensure that developers in the government sector are linked to the users through verification exercises and post-incident debriefings. In this manner, lessons learned through practical applications of the model can be incorporated in improvements and updates.

User ↔ Researcher

The third linkage shown in Figure 5.1 is that between the user and the researcher. It is perhaps the most tenuous communications pathway in the whole model development system. Ideally, the user would communicates his operational needs to the research community and the researcher would focus his/her efforts on particular deficiencies identified in an operational setting (e.g., the need to quantify a physical process to improve the mass balance estimates in an oil spill). Within Environment Canada, the Regional Environmental Emergency Coordinators can communicate priorities to the Environmental Sciences Division (ESD), and are given the opportunity to comment annually on ESD research proposals (J-P.

Auclair, pers. comm). PERD also plays a role here in supporting relevant government work.

In the private sector, the PERD programs provide an important link between industry and research. Over the past 5 years, PERD has increasingly sought industry input on research projects. There is a need for more communication concerning research timelines. Operational organizations typically work with timelines of one to two years, while PERD projects can run for 5 years. This can lead to conflicts, as in a recent industry request for PERD to develop an ocean current database for the Beaufort Sea Coop oil spill model (B. Wright, pers. comm.) Other than PERD, there are no other formal modelling linkages whereby the industry users can transmit their concerns to the research community as a whole.

5.1.1 An Example of an Integrated Model Development Process

Industry and government participants selected Applied Science Associates to further develop their World Oil Spill Model Shell to provide deterministic and stochastic spill forecast and receptor mode simulations for spill sites throughout the world. The model works on a basic 256 X 256 element grid and is limited in resolution only by the level of detail available for the input data (base maps, currents, wind fields etc.).

What makes the ASA model development unusual as an example of linkages is the high level of involvement by the participants in refining the prototypes as the model progresses. The participants act as the Technical Advisory Group (TAG) which meets for several days every 2 to 3 months; this process is expected to continue for the full two year time scale allocated to the project. Between meetings, the participants who tend to have specialized scientific backgrounds in relevant fields (e.g., oil chemistry or oceanography), run pre-release versions of the model within their own facilities. By removing bugs and unwanted features

as the model develops, the participants expect to receive a fully operational product at the end of the project.

The "World Oil Spill Model" development program has proven to be an effective vehicle for researchers, operators, users, and developers to interact on a regular basis as a new operational model framework evolves (Goodman; Devenis - pers. comm.) The pro-active role of the TAG overcomes the limitations of having different groups working in isolation or along single lines of communication.

5.2 Current Model Linkages

It was not possible to examine the current model research/operational linkages at the same level of detail as the oil spill trajectory models, as there are fewer operational current models available.

In fisheries management research, the users of current models (fisheries biologists) and model researchers (oceanographers) fall within the same Canadian government department and have naturally strong linkages, to the point of co-authoring research papers (e.g., Crawford et al., 1990).

A similar close professional relationship exists between researchers and developers involved in the implementation of current models (e.g., Seaconsult and IOS, MEP and BIO). The Department of Fisheries and Oceans has a formal mechanism for technology transfer through the Industrial Liaison Officers. Discussions with T. Courran (Industrial Liaison Officer at the Institute of Ocean Sciences) revealed that the funding available to encourage contracting-out has been cut dramatically. To his knowledge he is one of the only officers remaining with a budget, which he uses to fund projects on the order of $5,000. Recently he paired M. Foreman of the Institute with Channel Consulting through a small contract. That relationship worked out quite successfully, and resulted in an operational tidal model with a unique user-friendly visualization interface.

Historically there have been two linkages in place to facilitate the transfer of research current models into the operational arena within Canada, namely:

- the National Research Council of Canada (NRC), Program for the Industry/Laboratory Projects (PILP) (now IRAP)

- the Unsolicited Proposal (UP) fund (now defunct but in the process of being rejuvenated - October 1991)

The MEP Company used these mechanisms to develop the OCS; PILP supplied 60% of the necessary financial support in Phase I of the work and MEP assumed responsibility for the remaining 40%. Phase II was funded through a UP. The UP Program is no longer in existence and has left a serious gap in the available routes for technology transfer in Canada (recent proposals for its resurrection include only the brokerage aspects, and lack the important feature of bridge financing). The funding available to the Industrial Liaison Program has also been cut dramatically (see above).

In summary, the available levels of funding in Canada are inadequate to support the historical levels of activity linking the current model researchers with the commercial developers. These activities have been the primary driving force in moving current models from the research to the operational environment.

An international linkage exists within the research community through WOCE (World Ocean Circulation Experiment). This program involves data gathering and development of large-large scale (10's of km) ocean circulation models at various research centres worldwide. Canadian Universities and Department of Fisheries and Oceans research centres are participating in the program (P. LeBlond, pers. comm.). The objective of the program is to develop ocean circulation models in order to determine the contribution of oceans to the global heat budget. WOCE provides an international forum for exchange of

modelling techniques. Although the focus is large-scale, the procedures for improving the efficiency of numerical computation will apply to fine-scale models as well.

5.3 Wave Model Linkages

Researchers ↔ Developers

Wave model research and development falls either within the realm of the Atmospheric Environment Service (AES) or in the hands of a few researchers such as D. Resio, M. Donelan, or V. Cardone. Research/developer linkages are few because both functions are performed within most wave modelling groups. For example, AES, Oceanweather Inc., and D. Resio conduct both research and development of operational models. As discussed in Section 4, these groups tend to have a stable of models ranging from 1G (first generation) operational to 3G (third generation) research. Development is continually underway to further develop the research model and to bring components of that model into the operational model.

Research ↔ Operations

As discussed previously for oil spill trajectory models, AES has communication lines within the organization which are used to collect feedback on prototype and operational models. There are a number of groups within AES who have responsibilities for research, development, and implementation. For example, incorporating new research into the 3G CSOWM is undertaken by M. Khandekar, while the Systems Development Group develops the interactive forecaster interface for PACWAV (V. Swail, pers. comm.).

The National Wave Committee, chaired by V. Swail (AES), acts as a key linkage between wave researchers, modellers, operators, and users. The ad hoc committee consists of representatives from several agencies including AES, Department of Fisheries and Oceans

(IOS and BIO), Transport Canada, Department of National Defence, the National Energy Board, and Mobil Oil. The agencies not only represent research groups, but operators and end users as well. The committee has focused on wave research (through W. Perrie, M. Donelan, and D. Masson), wave hindcasting and forecasting (CSOWM) as well as the establishment of a regional model in the Pacific Weather Centre (PACWAV) (V. Swail, pers. comm.).

The Canadian research and operational community attends the annual meetings of the WAM group. WAM is an international group which meets to discuss the the entire range of wave modelling from research to operational. WAM provides an excellent linkage between operations and research. Dr. M. Khandekar attends the WAM meetings to collect ideas and research for implementation into the third generation CSOWM model. Another conference series, the International Workshops on Wave Hindcasting and Forecasting, have provided a forum for exchange between researchers and operations. WAM and the International Workshops series also provide an opportunity for linkages within the research community.

While AES continues to contract with Oceanweather, Inc. for work concerning the CSOWM model (M. Khandekar, pers. comm.), industry prefers to rely on outside contractors to develop and operate operational wave models (J. Spedding, pers. comm.). The strength of the linkage between operator and researcher varies from company to company. For instance, MacLaren Plansearch Ltd., who provided operational forecasts to the oil industry in the mid-eighties, is in a joint venture with Oceanweather, Inc. (the developer of ODGP). Oceanroutes (Canada) Inc. has less direct contact with Dr. D. Resio, the developer of WAVAD. In the case of industry, it is difficult to evaluate the effect of the operator/researcher relationship on operations.

User ↔ Researchers

Except for Mobil's participation in the National Waves Committee, there does not seem to be any definite communication link between users of wave models (e.g., industry or mariners)

and researchers. Companies which provide operational forecasts to these groups (i.e., Oceanroutes (Canada) Inc.) must operate by the elements of the marketplace to determine their user's true needs and to transfer these needs back to the original researchers.

5.4 Model Interrelationships

Operational current models in combination with wind data/models can provide oil spill trajectory models with accurate representations of surface currents carrying the oil (wind driven, residual and tidal). Other than trajectory predictions, current information is usually not required to run the algorithms describing other processes (e.g., evaporation and dispersion).

The importance of accurate, high resolution operational current models to oil spill trajectory models cannot be over stressed. In the absence of surface drifters, HF radar systems (which could provide real-time maps of surface currents), or other means of measurement, current and wind models provide the only source of high resolution driving force data. Ultimately, the trajectory predictions of the model are only as accurate as this input data (whether it be measured real-time or predicted from numerical models).

A linkage also exists between research current models and operational spill trajectory models. Research models are typically developed in as much detail as possible in order to gain an understanding of a region through the model predictions. Once this understanding has been verified, researchers or developers can then produce a model of surface transport based on the understanding of the circulation as a whole (i.e., as in the INRS modelling program for the St. Lawrence estuary). Another approach is to forgo the modelling of the entire water mass for increased observation and practical understanding of the surface regime.

Once completed, the surface transport research model can be coupled to an operational oil spill trajectory model in a user-friendly system. Additional refinement and simplification of the numeric code is usually required.

Wave models are of far less significance to oil spill trajectory models at present. Research has shown that the contribution of wave drift to surface currents is minimal as far as oil slicks are concerned, especially given the state-of-the-art in current modelling. If the approach of the recent research at Warren Springs Laboratory is verified (T. Lunel, pers. comm.), data on breaking waves may be required to predict droplet distribution and oil spreading in operational models.

Waves can be important in the processes of dispersion (e.g., Spaulding, 1988), and emulsification but the understanding of these processes generally falls far short of our ability to forecast wave spectra.

At this point in time, linkages between operational wave and current models are practically non-existent. Research is being conducted to determine the significance of current interaction with waves and to develop algorithms for incorporating current effects into wave models. For the reverse situation, the interaction of waves on currents, very little effort has been devoted in Canada to the modelling of wave-induced currents.

6.0 CONCLUSIONS

Oil Spill Trajectory Models

The numerical algorithms available to model the advection of oil on the water surface have surpassed the availability and resolution of current and wind data. Resources need to be allocated for the development of current models or the provisions of real-time measurements in order to improve this component of oil spill modelling.

Present research on evaporation, emulsification, dissolution, and other fate processes should result in improvements to fate sub-models over the next two to three years. Research presently being conducted at Warren Springs Laboratory in Stevenage, UK, may determine if the droplet modelling approach to spreading is more valid than the Fay's (1971) equation (equilibrium of surface tension, gravity, viscosity and inertia). Algorithms describing oil-in-ice interaction have been developed, but a serious lack of field data is hampering further refinements and verification.

In the near future, operational HF radar systems may be able to provide real-time surface current measurements for oil spill trajectory models.

User interfaces, output formats, computer configurations, and run times are generally sufficient for operational needs.

Ideally, both oceanographers and oil spill specialists (with a chemical background) need to be involved in the transfer of oil spill modelling research to the operational community. Developers need to appreciate that the final users of the model outputs are most likely to be oil spill response specialists who are primarily interested in a graphical "instant" presentation.

While AES has a formal mechanism for discussion between operators and developers, the linkage between the key government users (REEC's), and model developers is weak at present. Increased involvement of the developers in verification trials and post-incident debriefings will ensure that lessons learned during practical applications of a model are reflected in future updates and improvements.

Existing linkages between researchers and developers suffer from the process of remote communication through the published literature. This pattern may lead to omissions and errors in the way research algorithms are selected, incorporated, and applied in an operational model.

The pro-active approach being taken by the joint government/industry advisory group in steering the development of the new "World Oil Spill Model" is an effective means of involving all parties in the creation of an operational model (researchers, users, and developers).

Current Models

In spite of the need for operational current models to support oil spill trajectory models, only several of the models identified are presently set-up operationally. On the West Coast, tidal models for Juan de Fuca and Georgia Straits have far exceeded similar capabilities elsewhere in Canada. The Operational Ocean Current Modelling System (OCS) can predict surface currents on the Scotia Shelf but requires additional effort to become truly operational. Several consulting firms have the capability to develop specific applications from generic in-house models.

Current modelling research is concentrated on the development of baroclinic models on both the West and East Coasts, with more efforts being devoted to residual rather than tidal currents. The 2-dimensional method developed by M. Foreman and F. Henry at the Institute

of Ocean Sciences is being used by groups on both coasts to develop tidal models for commercial and research applications.

Mechanisms for transferring current models to the operational community have been affected by a loss of funds. Historically, both the Institute of Ocean Sciences and the Bedford Institute of Oceanography worked closely with consultants to transfer research results to the consultants, with the Department of Fisheries and Oceans providing partial funding to the consultant. Once the research results were moved into the private sector, operational applications such as search and rescue models or databases for oil spill trajectory models were developed. Researchers consulted estimate that the time frame to achieve operational models from the present research is significant: 5-10 years.

Wave Models

Operators of operational wave models have indicated that the ability to modify wind and pressure field inputs is crucial to the effectiveness of operational models. Their needs are driving the advancements of wave model interfaces and producing advanced data input systems. Model acceptance is a lengthy procedure as forecasters tend to continue to use wave nomograms until they have gained confidence in model performance (often for one to two years). This may be justified as it appears that the accuracy of CSOWM and PACWAV (two AES models) in operational settings is still comparable to simple wave nomograms used by experienced forecasters.

Variations of four operational wave models are in available for use in Canada: (1) ODGP (which is the source model for AES's CSOWM and PACWAV); (2) WAVAD, which is the source model for DWAVE; (3) Donelan's model; and (4) SPECREF. While models such as CSOWM have third generation versions incorporating shallow water physics, only first generation models using deep water physics are available operationally. Computational requirements are the primary factor limiting the development of more sophisticated operational models. As with oil spill trajectory models, operational models are hampered by

the quality of the wind data available. Data received from the ERS-1 satellite and programs such as SWADE should advance the understanding of wind-wave coupling.

Linkages in wave modelling are the strongest of the three types of models studied, with AES providing a focal point for international communication, as well as research-operations linkages. Again, the weakest link is between users (the oil and gas industry and mariners) and researchers.

Model Interrelationships

Oil spill trajectory models are strongly linked to current models due to the need for surface current information to drive the advection of the oil. Presently, wave models are not required by oil spill trajectory models. In the future the use of the droplet modelling approach for oil slicks and an improved understanding of wave processes in emulsification will increase the need for wave data. Models of current interactions with waves are being studied at the research level. None of the research or operational models reviewed predicted wave-induced currents in any depth.

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Horita, M.	AES Pacific Weather Centre, Vancouver
Khan, R.	C-CORE, St. John's
Khandekar, M.	Atmospheric Environment Service, Downsview
Lange, O.	AES Pacific Weather Centre, Vancouver
Lawrence, D.	Bedford Institute of Oceanography, Dartmouth
LeBlond, P.	University of British Columbia, Vancouver
Lunel, T.	Warren Springs Laboratory, Stevenage, U.K.
Signorini, S.R.	Greenhorne & O'Mara, Inc., Greenbelt, MD
Simmons, R.	Environment Canada, EP, Atlantic Region, Dartmouth
Spedding, J.	Esso Resources Canada Ltd., Calgary
Swail, V.	Atmospheric Environment Service, Downsview
Venkatesh, S.	Atmospheric Environment Service, Downsview
Wright, B.	Gulf Canada Resources Ltd., Calgary

APPENDIX

Contact List

Oil Spill Trajectory Models

Users, operators, model developers, and researchers contacted during the study

Contact	Organization, Location
J-P. Auclair	Environment Canada, EP, Ontario Region, Toronto
Bob Beale	AES Pacific Weather Centre, Vancouver
Billie Beattie	AES Atlantic Region, Bedford
Fred Beech	Environment Canada, EP, Pacific Region, Vancouver
Randy Belore	SL Ross Environmental Research Limited, Ottawa
Robert Britch	ENSR Consulting and Engineering, Anchorage, Alaska
Ian Buist	SL Ross Environmental Research Limited, Ottawa
George Comfort	Fleet Technology Ltd., Kanata
Peter Devenis	Canadian Petroleum Association, Calgary
Hussein El-Tahan	Crescent Consulting Ltd., St. John's
Merv Fingas	RRETC, Environment Canada, Ottawa
John Fraser	Consultant, Houston, TX
Jerry Galt	NOAA, Seattle, WA
Ron Goodman	Esso Resources Canada Limited, Calgary
Don Hodgins	Seaconsult Marine Research Ltd., Vancouver
Allan Holoboff	Esso Resources Canada Limited, Calgary
Bela James	Shell Oil Company, Houston, TX
Rafaat Khan	C-CORE, St. John's
Bob LaBelle	Minerals Management Service, Herndon, VA
Tim Lunel	Warren Springs Laboratory, Stevenage, U.K.
Donald Mackay	University of Toronto, Toronto
Roy McClymonds	Clean Coastal Waters, Long Beach, CA
Bruce McKenzie	Alaska Clean Seas, Anchorage, AK
Neil Parker	AES, Western Region, Edmonton
Sergio R. Signorini	Greenhorne & O'Mara, Inc., Greenbelt, MD

Randy Simmons	Environment Canada, EP, Atlantic Region, Dartmouth
Brian Smiley	Institute of Ocean Sciences, Sidney
Malcolm Spaulding	Applied Science Associates, Inc., Narragansett, RI
S. Venkatesh	Atmospheric Environment Service, Downsview
Claire Wilson	Gulf Canada Resources Ltd., Calgary
Brian Wright	Gulf Canada Resources Ltd., Calgary

Current Models

Users, operators, model developers, and researchers contacted during the study

Contact	Organization, Location
Craig Bishop	Canada Centre for Inland Waters, Burlington
Terry Courran	Industrial Liaison Officer, Institute of Ocean Sciences, Sidney
Bill Crawford	Institute of Ocean Sciences, Sidney
Adrian Dolling	Channel Consulting, Victoria
Mona El-Tahan	C-CORE, St. John's
Mike Foreman	Institute of Ocean Sciences, Sidney
Richard Greatbacht	Memorial Universtiy of Newfoundland, St. John's
Paul Hamblin	Canada Centre for Inland Waters, Burlington
Mike Kelly	Coast Guard, Ottawa
Vladimir Koutitonsky	Institut Nationale de la Recherche Scientifique
Don Lawrence	Bedford Institute of Oceanography, Dartmouth
Paul LeBlond	University of British Columbia, Vancouver
John Loader	Bedford Institute of Oceanography, Dartmouth
Sylvain de Margerie	ASA Consulting Ltd., Dartmouth
John Pallister	DND Search and Rescue Coordination Centre, Esquimalt
Jim Stronach	Seaconsult Marine Research Ltd., Vancouver
Jeff Spedding	Esso Resources Canada Ltd., Calgary
Tom Yao	ASA Consulting Ltd., Dartmouth

Wave Models

Users, operators, model developers, and researchers contacted during the study

Contact	Organization, Location
Tom Agnew	Atmospheric Environment Service, Downsview
Alan Bealby	Atmospheric Environment Service, Downsview
Ross Brown	Atmospheric Environment Service, Downsview
Vince Cardone	Oceanweather, Inc., Cos Cob, CT
Steve Clodman	Atmospheric Environment Service, Downsview
Mark Donelan	Canada Centre for Inland Waters, Burlington
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Don Hodgins	Seaconsult Marine Research Ltd., Vancouver
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Owen Lange	AES Pacific Weather Centre, Vancouver
Gary Lions	METOC, Halifax
Etienne Mansard	National Research Centre Hydraulics Laboratory, Ottawa
Diane Masson	Institute of Ocean Sciences, Sidney
Will Perrie	Bedford Institute of Oceanography, Dartmouth
Donald Resio	Florida Institute of Technology
Val Swail	Atmospheric Environment Service, Downsview
L. Wilson	Atmospheric Environment Service, Downsview